POLITECNICO DI TORINO

Master of Science in Engineering and Management (Class LM-31)
Department of Management and Production Engineering

Degree Thesis

Towards Scalable and Repeatable Production: Process Optimisation in 3D Construction Printing at COBOD

Supervisor:
Professor Giulia Bruno

Candidate:
Mouna El Achari
331411

A.y. 2024/2025

اصبر على مرّ الجفا من معلمٍ
فإنّ رسوبَ العلمِ في نفراتهِ
ومن لم يذق مُرّ التعلّمِ ساعةً
تجرّع ذلّ الجهل طولَ حياتِه

—— *Il giurista Al-Shafi'i (767 – 820 d.C.)*

"Sopporta l'asprezza e la severità del maestro,
poiché le radici del sapere si trovano nelle sue difficoltà.
E chi non assapora l'amarezza dell'apprendimento per un'ora,
berrà l'umiliazione dell'ignoranza per tutta la vita."

INDEX

Abstract

This thesis explores the optimisation and standardisation of production processes within COBOD International, a global leader in 3D construction printing. While the technology of additive manufacturing in construction offers transformative opportunities for scalability, flexibility, and sustainability, it also introduces significant organisational challenges when moving from experimental projects to industrial-scale production. The study addresses these challenges by focusing on the Production Department of COBOD, where high variability, non-standardised practices, and dependence on individual expertise often generate inefficiencies and delays.

The research adopts a structured methodology that combines literature review, direct observation, process mapping, and interviews with key personnel. Lean Manufacturing principles serve as the theoretical framework, providing tools to analyse waste, variability, and workflow disruptions. Process analysis techniques such as SIPOC diagrams, spaghetti charts, and Value Stream Mapping were applied to assess the current state, identify bottlenecks, and quantify inefficiencies. A particular emphasis was placed on the role of ERP systems, BOM standardisation, and the integration of visual and procedural standards as enablers of process repeatability.

The empirical analysis highlighted recurring problems, including lack of updated documentation, poor stock management, and misalignment between departments. These weaknesses were linked to time losses in assembly, errors in part delivery, and difficulties in quality control. The study proposes a series of interventions: extended Standard Operating Procedures and checklists, improved ERP and BOM usage, and cross-training strategies to balance mechanical and electrical resources. Special attention was given to internal logistics and layout design, as the company prepares to relocate production to a new facility in Taastrup. Two alternative layouts were developed: a linear flow configuration optimised for clarity and minimal transport, and an alternative configuration that integrates an R&D and material laboratory to foster communication and flexibility.

The results demonstrate that structured process standardisation, combined with lean practices, not only reduces inefficiencies but also strengthens scalability, quality, and resilience. The proposed layouts offer different strategic advantages: linearity and simplicity in the first case, flexibility and integration of innovation functions in the second. Both options underline the importance of spatial organisation as a driver of efficiency and knowledge sharing.

In conclusion, the thesis contributes to bridging the gap between pioneering additive manufacturing practices and industrial-scale repeatability. By adopting lean-based standardisation, COBOD can improve its operational stability, reduce waste, and sustain its competitive position in a rapidly growing sector. Beyond the case study, the findings highlight the relevance of standardisation as a dynamic, enabling tool for innovation in complex and variable environments, offering insights applicable to other emerging industries undergoing industrialisation.

CHAPTER 1: Introduction

1.1 General context: 3D printing in the construction industry

In recent years, 3D printing, also called additive manufacturing, has grown rapidly across many industrial sectors, moving well beyond its first uses in rapid prototyping and conventional manufacturing. Among the industries affected by this development, the construction sector has gained particular attention. Traditionally, construction has been seen as one of the least technologically advanced industries, often defined by slow, labour-intensive, and time-consuming processes. The rise of Construction 3D Printing (C3DP), however, introduces the possibility of a more dynamic, faster, more precise, and above all more sustainable approach. This new method has the potential to transform not only the design of buildings but also the automation of construction processes, by reducing intermediate steps and improving the efficiency of resource use.

A distinctive advantage of this technology is its ability to produce complex geometries without depending on the heavy and rigid methods of traditional construction. The progress of C3DP is made possible by advances in additive technologies, which allow the creation of three-dimensional objects through the layer-by-layer deposition of materials, guided by digital models. In practice, C3DP uses the extrusion of cement-based compounds through portal and gantry systems, controlled by software that translates digital designs into machine instructions. The outcome is the accurate reproduction of digital models in physical form, with a precision that traditional methods cannot achieve.

Despite these advantages, C3DP also faces important challenges, especially when moving from experimental or small-scale projects to industrialised and repeatable production. For this reason, the development of solid organisational structures and the standardisation of production processes are essential. These elements are necessary to ensure efficiency and scalability, while at the same time keeping the flexibility and adaptability that are the main strengths of 3D printing.

1.2 COBOD International: innovation in 3D printing for construction

In this evolving context of the construction sector, COBOD International has established itself as one of the most innovative and dynamic companies on a global scale. Founded with the explicit aim of applying Construction 3D Printing (C3DP) at an industrial level, the company has developed modular printers designed to operate over large areas through a dimensional structure that can be customised according to specific project requirements.

The BOD series printers, developed entirely in-house, represent a benchmark of technological excellence in the field of construction-scale 3D printing. Their modular architecture, allowing for the installation of 2, 4, 6, or 8 legs depending on the operational area, ensures both flexibility of application and significant variability in internal production. In recent years, this technology has attracted growing interest from international customers, leading to increasing demand for larger and more advanced models such as the BOD 3 and BOD XL.

This expansion has, however, brought with it new organisational and operational challenges. To meet rising expectations and ensure repeatability of production, COBOD has been to reconsider and reorganise its internal processes. The company therefore stands at a strategic turning point: on the one hand, the opportunities of global market expansion; on the other, the necessity of consolidating its organisational capabilities to support industrial scalability and long-term competitiveness.

1.3 The challenge: standardisation of production processes

In this context of product development and diversification at COBOD, the need to standardise the processes of the Production department has become increasingly evident. At present, many operational activities are managed in a predominantly manual and non-standardised manner, supported by limited documentation and heavily reliant on the skills of individual workers. While such an approach may prove effective during an initial pioneering phase, it becomes a significant bottleneck once the company seeks to scale up its operations.

Two main factors underline the urgency of introducing operational standards:

1. Diversification of BOD models

   The growing number of BOD versions and the development of more complex variants inevitably require more elaborate processes and greater coordination between activities. Standardising production phases reduces variability, ensures greater consistency, and ultimately enhances quality.

2. The imminent transfer of the production site

   COBOD is preparing to transfer its entire production to a new facility in the coming months, with spatial and layout characteristics different from the current site. In this scenario, the existence of standardised processes will allow for a quicker and smoother adaptation, minimising the risk of inefficiencies or slowdowns during the transition.

Standardisation, therefore, is not only seen as a control and quality tool, but as an enabler for the future growth and flexibility of the organisation.

1.4 Objective

The objective of this thesis is to analyse the current configuration of the production processes within the Production Department of COBOD and to propose a standardisation pathway consistent with the principles of Lean Manufacturing. In particular, the study aims to identify critical areas in terms of operational variability, inefficiency, or lack of structure, and to suggest solutions that may also be applied in the new production facility.
The thesis adopts a qualitative approach, based on direct observations, documentary analysis, and comparison with the technical literature.

CHAPTER 2: Theoretical Framework

2.1 Definition, Purpose and Typologies of Standardization

"Standardization is the activity of establishing and recording a limited set of solutions to actual or potential matching problems directed at benefits for the party or parties involved balancing their needs and intending and expecting that these solutions will be repeatedly or continuously used during a certain period by a substantial number of parties for whom they are meant" (Vries 1999, 155).
This is the definition provided by the International Organisation for Standardisation (ISO), which encapsulates the essence of standardisation in a strategic process. It is not just a matter of bureaucracy, but of ensuring consistency and stability in complex and dynamic systems. Standardisation can be defined as the process adopted by an organisation to define consistent and repeatable operating methods, with the aim of minimising variability while ensuring maximum quality and compliance with technical and quality requirements.
Standardisation has always been associated with large-scale industrial production, but today the concept is applicable to quality and lean production systems. In a more modern view, standardisation consists of making an activity visible and transferable throughout the organisation, documenting all steps to eliminate variability.
Various types of standards are defined in the production field, classified by level of formalisation:

- Documentary Standards

Formalised documents such as technical manuals, operating protocols, quality analyses, and compliance regulations. These ensure that outputs conform to predefined technical specifications.

- Operational Standards (SOPs – Standard Operating Procedures)

These clearly and formally specify the sequence of operations, tools, materials and safety rules to be followed to carry out an activity. They guarantee the repeatability of processes and the training of personnel, especially in manual and complex contexts.

- Visual Standards (Visual Management Tools)

Tools such as signage, information panels, and labelling that facilitate the organisation and coordination of work, support decision-making, and enable the rapid identification of errors.

- Behavioural Standards

Unwritten conventions and practices adopted within the organisation. While less rigid, they ensure structural consistency in staff behaviour and process execution.

- Product or Component Standards

These define the dimensional, material or functional characteristics of parts and products. They serve to ensure the compatibility, interchangeability and conformity of components throughout the production and supply chain, often aligning with international standards (e.g. ISO, DIN).

- Performance Standards

These are essential for measuring process efficiency and comparing it with pre-established objectives. They refer to expected results, such as takt time, cycle time or acceptable defect thresholds.

Standards not only certify performance control, but are also an essential lever for ensuring safety, operational consistency and the achievement of established objectives, both for organisational growth and industrial evolution.

2.1.1 Advantages and limitations

Standardised procedures applied to the production context yield a series of measurable benefits, both from a technical and an organisational perspective. Among the most evident advantages is the reduction in variability, achieved through the uniformity of executive procedures that enable constant implementation control, thereby reducing errors, waste, and rework. The application of standards increases process efficiency, ensuring stability and order in work environments undergoing transition, where the risk of inconsistency between departments is higher.

Another significant advantage is the facilitation of training. Through SOPs, performance can be structured in a more systematic way, making training more organised, promoting staff integration, and reducing reliance on key figures. Furthermore, standardisation strengthens quality control, as it imposes predefined parameters of acceptability and the implementation of monitoring systems in critical phases.

From a management and organisational standpoint, standards also simplify data analysis, allowing performance to be monitored through relevant KPIs and ensuring overall process consistency and reliability. Nevertheless, despite this range of benefits, standardisation may also generate rigidity when schemes are excessively detailed. In such cases, it can hinder adaptability in unusual circumstances, making the system less responsive to new requirements or unforeseen events.

The introduction of standards within a system is not always straightforward, as it entails initial implementation costs that include not only process analysis and documentation, but also staff training. The latter may give rise to cultural resistance, particularly among senior operators who perceive standardisation as a limitation of their autonomy.

Finally, it is important to regard standardisation as a revisable process, continuously supported by a system of improvement, in order to mitigate the risk of obsolescence in constantly evolving environments.

2.1.2 Standardization in dynamic environments

The usefulness of standardisation must also be measured by considering the context of application. Traditional organisations have a process structure that is not subject to change and evolution, characterised by high repetitiveness and low variability; in this environment, the application of standards is less complex and more versatile. On the contrary, in today's more dynamic production context, an approach that guarantees uniformity and adaptability is essential. This is referred to as flexible standardisation, a model capable of providing a precise and uniform framework, but also capable of handling variations, ensuring a constant flow.This approach is particularly useful in growing companies, where products are not homogeneous or production layouts are subject to reconfiguration. Not all stages of a process can be standardised. For example, contexts that work on products with different configurations apply standards to common activities (e.g. cabling, initial testing, etc.), while specific activities are

treated as variants, with additional documentation. In this world, standardisation is not seen as a constraint but as an enabling tool, which does not reduce the flexibility of the process but provides a solution that can be adapted to various needs.
Therefore, it is not just a lever for efficiency, but also for organisational resilience.

2.2 Techniques for Process Analysis

In order to effectively standardise operational procedures, it is essential first to know and understand the processes within the system. Process and flow analysis constitutes a prerequisite for implementing improvements, reducing inefficiencies, and gaining a comprehensive understanding of the manoeuvres and actions that characterise the operational context. Accordingly, process analysis represents the initial step, consisting of mapping workflows, visualising bottlenecks, and identifying waste and variability.
In traditional systems, data collection is generally based on structured concepts such as cycle times, takt times, and operator workloads. However, the working environment does not always permit this type of information gathering. In some contexts, work processes may not have fixed cycle times or static workstations, or they may be characterised by low levels of automation. In such circumstances, data collection can prove complex, but it is important to emphasise that standardisation is not measured in terms of cycle time, but rather in the repeatability of actions and the stability of interactions between operators, materials, and tools.
This section examines a number of process analysis methods applied in production contexts marked by high variability in inputs or demand, or by limited availability of observations. It begins with an overview of qualitative mapping tools such as the SIPOC diagram and the use of flowcharts, before proceeding to a description of Value Stream Mapping (VSM), one of the principal Lean tools used to distinguish value-adding activities from those that generate waste. Finally, when detailed quantitative data are lacking, qualitative methods and mechanisms of continuous improvement cycles, such as PDCA and root cause analysis, are employed as valuable alternatives.

2.2.1 SIPOC Methodology for Process Mapping and Improvement

SIPOC is an essential tool in business process management and fundamental in the context of continuous improvement techniques such as Six Sigma. The latter is a structured management approach, developed in the 1980s at Motorola and made famous by General Electric, which aims to improve the quality of business processes by reducing errors and variability. The name

Six Sigma refers to the statistical performance level of a stable and precise process, capable of producing no more than 3.4 defects per million opportunities. The goal is therefore to achieve high operational levels through the application of qualitative tools that allow processes to be analysed, optimised and controlled.

A central role in this methodology is played by DMAIC, an acronym for Define, Measure, Analyse, Improve and Control, a structured sequence to guide improvement.

In the Define phase of the DMAIC cycle, the problem, objectives and project limits are identified. In the Measure phase, the data necessary to quantify the performance of the process is collected. In the Analyse phase, the main causes of inefficiencies are investigated. In the Improve phase, the solutions studied are defined and implemented. Finally, in the Control phase, control systems are established to ensure that the results achieved are maintained over time. In this system, SIPOC is used in the Define phase because it allows the process to be mapped and described at a macro level, specifying boundaries and the actors involved. *(*Figure 1).

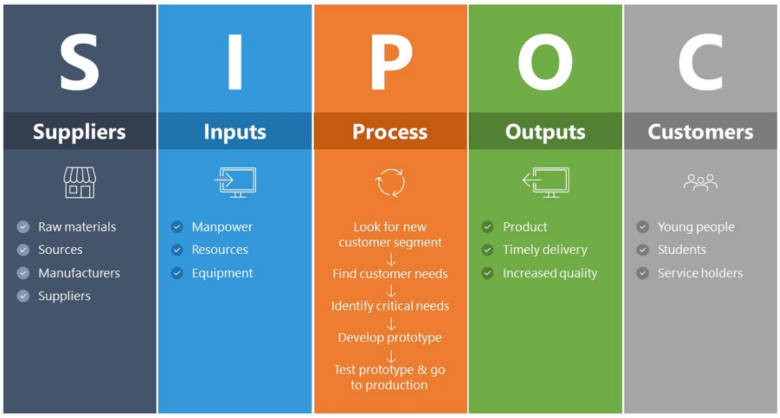


Figure 1:SIPOC process (Source: SIPOC Six Sigma Methodology/)

SIPOC works by compiling a table structured according to various key elements: process, purpose, owner, SIPOC and boundaries *(Figure 2)*.

- Process details the specific activities that characterise each phase
- Purpose defines the purpose of each phase, identifying the added value generated for the company.
- Owner represents the person responsible for the phase, i.e. the person who ensures that the phase is carried out correctly.

- SIPOC, an acronym for Supplier, Input, Output and Customer, identifies respectively the suppliers who provide the necessary resources, the material or information inputs, the outputs produced and the customers who receive these outputs.
- Boundaries delimits the boundaries of the process, identifying where the process begins and ends, avoiding overlaps or gaps in mapping.

SIPOC Process Definition Template:

Process:				
Purpose:				
Owner:				
Suppliers	**Inputs**	**Process Steps**	**Outputs**	**Customers**
Boundaries:				
Start-point:		End-point:		
Includes:		Excludes:		

Figure 2:SIPOC Process definition template (Source: Improvement Skills Consulting Ltd., 2008)

Compilation is not just a technical activity; it requires the involvement of various company stakeholders with an operational approach in order to ensure accuracy and a shared vision of the process. Once compiled, the SIPOC also provides strategic support for improvement, allowing the identification of redundancies, critical issues and inefficiencies. In the Six Sigma context, thanks to the DMAIC application, the SIPOC provides the basis for the subsequent Measure and Analyse phases, clarifying what needs to be controlled.

Sipoc therefore not only provides a clear and precise operational vision but also allows for a more in-depth analysis of the stages of a process, and when combined with flowcharts or concept maps, it also promotes clear and shared communication, facilitating strategic alignment.

2.2.2 Flow chart

The flow chart is one of the most widely used graphical tools for representing processes. Its main usefulness lies in its ability to provide a graphical and logical view of the sequential activities, decisions and information flows that characterise operational evolution, making a complex process immediately understandable through the use of a standardised language that allows key points and decisions, inputs, outputs and interconnections to be identified.

Flow charts were originally developed in the context of industrial engineering and computer programming, but thanks to their clarity, they have gradually become a basic tool in Business Process Management and beyond.

From a methodological point of view, the flow chart is divided into three phases:

- Recognition of the process from figures, with the definition of boundaries
- Breakdown of the system into basic operations, identifying the steps and decisions essential to the success of the process
- Graphical translation into standard symbols provided by ANSI and ISO to ensure universal readability

Standard flow chart symbols

To ensure unambiguous interpretation, flow charts use standardised symbols, i.e. conventional geometric shapes, each with a specific meaning, defined by ANSI (American National Standards Institute) and ISO (International Organisation for Standardisation). Figure 3 provides a general overview of the most common symbols.

Oval(terminator)

Identifies the start or end of a process. Each flow chart must contain at least one start point and one end point. Example: "Order received" (start), "Product delivered" (end).

Rectangle(process/activity)

Defines an activity or operation to be performed. It is the most commonly used element, as it describes the main actions of the flow. Example: 'Prepare materials', 'Assemble module'.

Rhombus(decision)

Symbol dedicated to a decision point, where the flow can follow alternative paths based on a condition. The outgoing arrows typically show binary answers ('Yes/No'). Example: "Is the component compliant?".

Parallelogram(input/output)

Used to represent input data (e.g. customer orders, technical specifications) or output data (reports,
documentation, information systems).

Arrow(flow,connector)

Defines the direction and sequence of the process, connecting the various symbols. Ensures linearity and readability in the representation.

Circle(internal/externalconnector)

Used to connect parts of the diagram on different pages or at distant points in the drawing, avoiding overly long or crossed lines.

Document (stylised sheet)

Represents the production or use of paper or digital documents (e.g. test reports, certifications).

Archiving symbol

Used to represent the storage or retrieval of data from a computer system or physical archive.

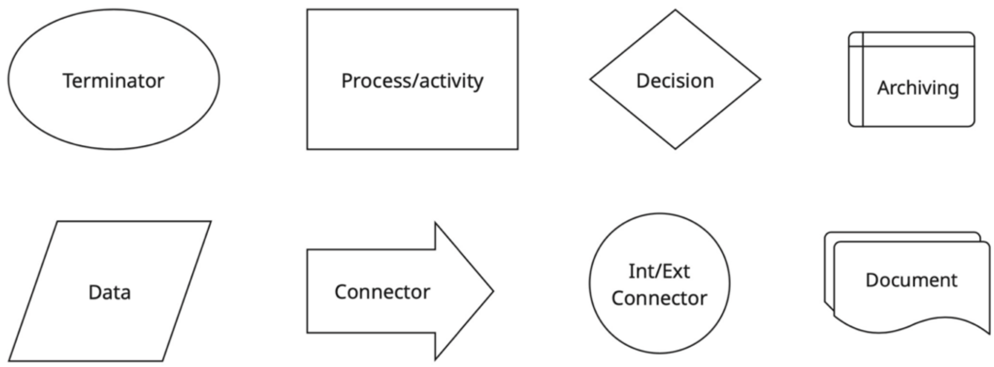


Figure 3:Flow chart symbols

Flow chart structure

As we have seen, flow charts follow a precise pattern based on clarity and linearity:

- Top-down or left-right: the flow chart develops from top to bottom or from left to right

- Clear labelling: each symbol contains a brief, clear description, without too many details, which would make the diagram confusing. For more complex processes, multi-level diagrams are used
- Decisions: diamonds must always have two or more outputs
- A single start and end: an essential condition to avoid ambiguity
- A well-constructed flow chart follows rules of clarity and linearity:

A practical example is shown in Figure 4, where a simple order process flow is represented with standard symbols: user registration (input) generates an order and the subsequent payment request, thus activating a process where activities are carried out in sequence (rectangles). Any payment requests lead to decisions (diamonds), and the request is processed (end).

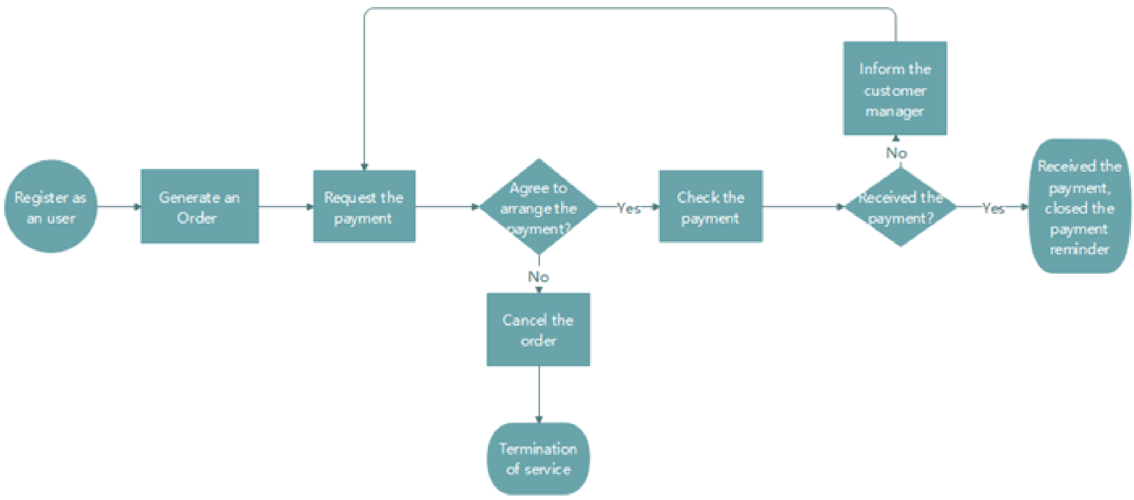


Figure 4:Process order flow

2.2.3 Value Stream Mapping (VSM)

Value stream mapping is a tool that provides an overview of the entire system, not only value-added activities, but also waste and inefficiencies, including temporal and quantitative aspects, unlike flow charts and other mapping tools that focus only on logical sequences.

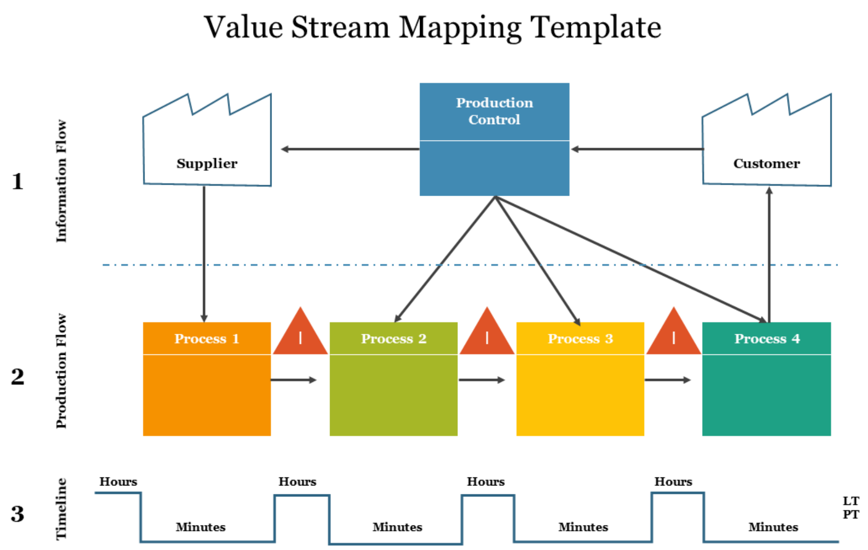
VSM is therefore considered one of the central tools of lean thinking, an organised method for analysing and improving the internal flows of a process.

The organisation of flow mapping has two phases:

1. As-Is map identifies the current state of the process, highlighting bottlenecks, delays and waste
2. To-be map illustrates a future scenario in which flows are optimised and aligned with lean principles

The data and information studied are collected through direct observation, interviews and, if available, quantitative data. A VSM map contains (Figure 5):

- Information flow, from supply to final customer
- Production flow, communication between departments, ERP systems, etc.
- Timeline, classification of times into value-added (VA) and non-value-added (NVA) activities



<u>Figure 5:</u>Value Stream Mapping template (Source: SlideEgg, 2025, available at www.slideegg.com)

In an industrial environment where processes do not follow constant machine cycles or rigid production standards, data collection is complex. In these contexts, VSM must be qualitative in nature, focusing on main flows and interactions, despite estimated time measurements. This approach ensures that, even in the absence of precise timed data, it is possible to provide a common language for continuous improvement, facilitating communication between operators and managers, identifying redundancies, inefficiencies and opportunities for development. Periodic use can also be useful for monitoring the future scenario and the condition of processes.

2.2.4 Time and Method Analysis

It is a traditional tool for standardising production processes, dating back to Scientific Management and the motion studies of Frederick Taylor and Frank and Lillian Gilbreth.

Time and Method Analysis is one of the most traditional tools for studying and standardising production processes. Its origins date back to the work of Frederick Taylor and Frank and Lillian Gilbreth, pioneers of Scientific Management and motion studies. The main objective of

this approach is to measure the execution times of different operations, analyse the methods used by operators and identify opportunities to improve efficiency and reduce waste.
Time studies traditionally involve determining a standard average time through observation and repeated timing of the various activities in a process. The result is then corrected with evaluation factors related to operational requirements and variations. Method analysis focuses on the study of movements, with the aim of eliminating cumbersome steps by rationalising sequences and promoting ergonomics.
However, time studies encounter limitations in processes with a low degree of repetitiveness, where the work is mainly manual and the tasks change depending on the product and the team; precise time measurement is difficult to replicate or of little significance. In this context, the analysis focuses on a more qualitative than quantitative study, favouring direct observation and the collection of narrative evidence over the definition of standardised times.
Despite these difficulties, time and motion analysis remains an important reference for continuous improvement, especially when integrated with more flexible tools, such as process mapping or visual standardisation techniques. In this way, even in complex contexts, it is possible to use the principles of time and motion analysis as a guide for structuring processes, without applying them rigidly.

2.2.5 Qualitative tools for standardization

Qualitative tools play a crucial role in standardisation and in the creation of shared knowledge, as they make it possible to analyse and improve processes even in the absence of precise numerical data. Their effectiveness lies in observation and systematic study, allowing processes to be represented and optimised in a way that is both pragmatic and adaptable.
One of the most widely used tools is the spaghetti diagram, which graphically represents the physical movements of operators, materials and equipment within the workspace. By tracing each actual movement, inefficiencies such as excessively long or repetitive routes and poorly designed layouts become visible. This simple tool can be applied without the need for measurements or numerical data, relying solely on direct observation of the process. In this sense, the spaghetti diagram not only supports optimisation but also contributes to the reduction of waste related to unnecessary transport and movement, aligning closely with lean philosophy, which will be discussed in the following chapter (Figure 6). The main objectives of this tool can be summarised as the identification of unnecessary and repetitive paths, which represent a waste of motion and transportation, and the highlighting of critical points within the layout. At

the same time, it serves as a support for the design of more ergonomic configurations and contributes to the reduction of time lost in non-value-adding activities, such as unnecessary movements, waiting, and inefficient transportation.

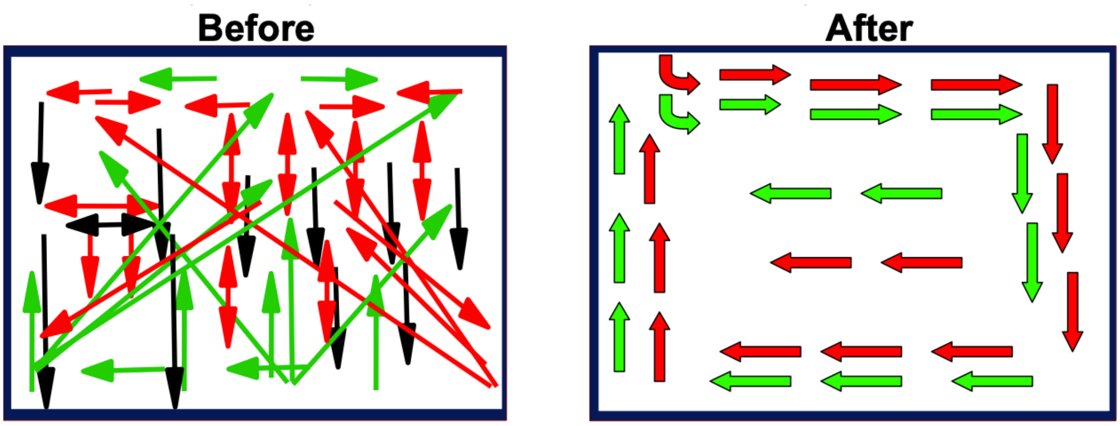


Figure 6:Example of Spaghetti Diagram (Source: "LSS Tool – The Spaghetti Diagram", Improvement Skills)

A second qualitative approach is the Standard Work Combination Table (SWCT), which provides a structured method for visualising the relationship between manual work, machine work, and waiting times. Its distinctive value lies in the way it translates complex operational dynamics into a single, coherent diagram that is immediately interpretable. Instead of relying on highly precise time measurements, which are often impractical in variable or manual-intensive contexts, the SWCT allows the use of ranges or estimates, making it especially adaptable to organisations operating in dynamic environments. (Figure 7).

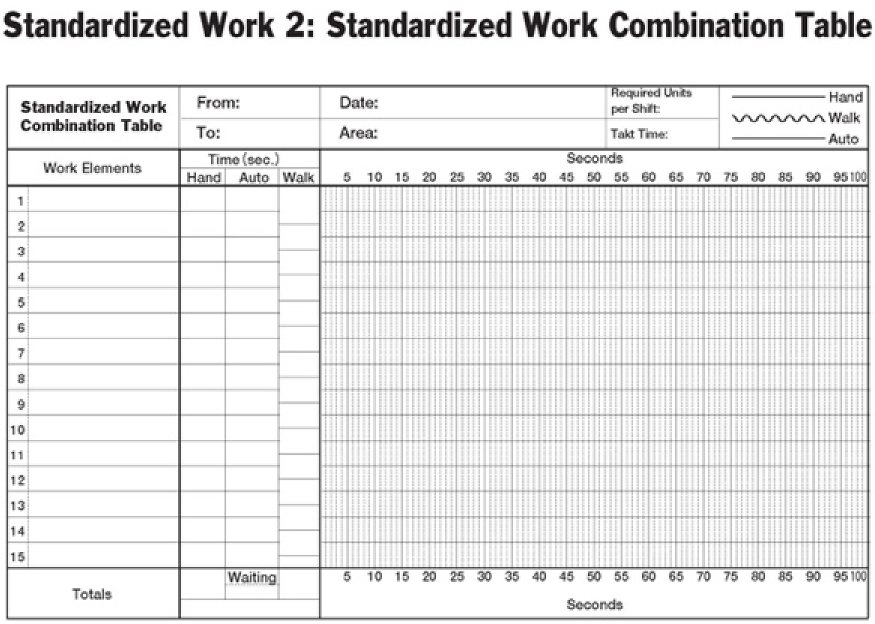


Figure 7:Standardized Work Combination Sheet (Source: 6Sigma.com, 2025, available at www.6sigma.com)

The structure of the SWCT typically takes the form of a timeline in which different categories of time are represented with distinct symbols or bars.

This layout makes it possible to identify overlaps and gaps: moments when the operator is fully engaged, when machines are running independently, and when idle times occur. Such clarity allows inefficiencies to emerge at a glance, facilitating targeted interventions. For instance, an operator's waiting time during a machine cycle might be utilised for secondary tasks, thereby improving the overall balance of activities. Similarly, if multiple operators are compared, the table can highlight uneven distributions of workload and support decisions regarding task reallocation.

From a managerial perspective, the SWCT functions as an essential decision-making and planning instrument. It allows for the simulation of multiple scenarios: what would happen if tasks were reorganised? How would productivity change if an additional operator or machine were introduced? Could waiting periods be converted into value-adding activities? By answering these questions, the SWCT does not merely document the current state of operations but actively guides the design of more efficient future states. This makes it not just a descriptive tool, but a prescriptive one.

Another dimension of the SWCT that is often emphasised in the literature is its role in training, standardisation, and communication. For new employees, a visually structured table provides an accessible introduction to how tasks are sequenced and balanced, enabling them to understand quickly where their contribution fits within the broader process. For experienced operators, the SWCT acts as a reference that reinforces consistency, reduces ambiguity, and ensures adherence to established standards. For supervisors, it provides a common language to communicate expectations, identify deviations, and support continuous improvement initiatives.

Ultimately, the SWCT plays a dual role: on the one hand, it is a technical instrument for identifying inefficiencies and rebalancing tasks; on the other hand, it is a cultural driver, reinforcing the principles of standardisation and lean philosophy by making process logic explicit and visible. Its strength lies in this integration: rather than being confined to process analysis, it becomes a means of organisational learning and alignment. By bridging the gap between observation, planning, and execution, the SWCT represents a cornerstone among qualitative tools for process standardisation and remains particularly valuable in production contexts where variability and adaptability are the norm.

Alongside process representation tools, the literature emphasises the importance of formalisation through Standard Operating Procedures (SOPs) and checklists. SOPs are documents that provide step-by-step instructions and rules describing the execution of an activity, ensuring consistent outputs and reducing variability. Checklists, on the other hand, serve as a practical instrument that guarantees accuracy in verifying the phases of a process, thereby minimising or eliminating the risk of errors or omissions. Both systems do not require complex quantitative data, yet they play a fundamental role in defining shared standards and disseminating good operational practices.

The drafting of a SOP typically follows a structured format to ensure clarity and usability:

- Title and identification code - every SOP must include a clear title, a progressive number or unique code, and the date of issue or revision.
- Purpose and scope - a concise description of the document's objective and the activities it covers.
- Roles and responsibilities - specification of who is responsible for performing the activities and who is accountable for supervision.
- Materials and equipment - a list of resources to be prepared before starting the activity.
- Step-by-step procedure - a numbered sequence of operations, written in a clear and concise manner, using imperative verbs (e.g. "Switch on the machine", "Check the oil level").
- Quality and safety criteria - any checks to be carried out and measures to ensure risk prevention.
- Attachments and references - control sheets, forms, internal regulations or external standards.

Best practices further recommend supporting textual instructions with images, diagrams, or checklists, which enhance visual comprehension and reduce the likelihood of misinterpretation. In this way, an SOP becomes not only a prescriptive document but also a practical tool that can be easily applied in the workplace.

Closely related to SOPs is the concept of visual management, a tool designed to make processes clear and transparent across all levels of the organisation. Its underlying principle is that critical information should be immediately visible, without requiring complex explanations, so that operators, technicians, and managers can all be fully aware of the process status. Visual signals integrate communication into the operational flow, making abstract concepts - such as material availability, tool allocation, order progress, or process anomalies - tangible through colours, indicators, and symbols. This approach simultaneously reduces misunderstandings and empowers operators, enabling them to monitor and correct their own activities without reliance on external supervision.

Examples of visual management are numerous. Andon systems, for instance, use lights or signals to highlight problems in real time, allowing prompt intervention. Shadow boards, with tool outlines clearly displayed, enable workers to identify immediately whether equipment is missing, thereby eliminating wasted search time and improving overall flow efficiency. Similarly, floor markings and colour coding guide movement within the workplace and ensure spatial organisation. In more advanced contexts, visual dashboards are employed to display key performance indicators, facilitating comparisons between targets and actual results. The effectiveness of visual management lies not only in simplifying daily activities but also in contributing to the development of an organisational culture centred on discipline and transparency. A visually structured workplace makes deviations from standards immediately evident, making it difficult to overlook anomalies. At the same time, it accelerates the training of new employees, who can quickly learn procedures simply by observing the visual organisation of the workspace.

For these reasons, visual management is widely recognised as a cornerstone of lean practices and continuous improvement programmes. It not only supports standardisation but also amplifies its effects, translating abstract standards into tangible and visible signals, thereby bridging the gap between theory and practice.

In order to provide a clear overview of the main qualitative tools discussed, Table 1 summarises their key functions, strengths, and limitations. This comparative framework highlights the distinctive contribution of each method, supporting the selection of the most appropriate tool according to the specific objectives of process standardisation.

<u>Table 1</u>:Comparative Table of Qualitative Tools

TOOL	FUNCTION	STRENGHT	LIMITATION
Spaghetti Diagram	Visualise physical flows of operators, materials, and equipment within a workspace to detect inefficiencies and redundant movements.	Simple, intuitive; does not require numerical data; highlights layout and ergonomic issues.	Provides qualitative rather than quantitative insights; becomes messy with many paths.
SWCT	Show interaction of manual work, machine time, and waiting periods on a timeline to balance workloads and identify inefficiencies.	Supports scenario analysis; versatile for decision-making; strong training and communication tool.	Requires at least rough time estimates; less effective without operator engagement.
SOP & Checklists	Formalise procedures step-by-step to ensure consistency, reduce variability, and provide a reference for training and verification.	Clear, prescriptive; easy to follow; ensures compliance and reduces errors or omissions.	Can become bureaucratic if overly detailed; effectiveness depends on compliance.
Visual Management	Use visual signals (colours, symbols, boards, dashboards) to make process visible.	Increases transparency; reduces misunderstandings; facilitates discipline and continuous improvement.	Implementation requires consistency; may lose impact if overloaded with signals.

2.3 Standardization and Continuous Improvement

The discussion developed in this chapter demonstrates that standardisation should not be regarded as a mere formal exercise, but rather as an organisational lever that renders work visible, repeatable, and measurable. By giving explicit form to knowledge that is often tacit, standardisation not only reduces unnecessary variability but also shortens learning curves, stabilises the expected level of quality, and lessens dependence on individual key skills. In this sense, the standard becomes the fundamental unit of operational governance:

- It clarifies responsibilities and interfaces;
- It enables process control through consistent indicators (e.g. lead times, defect rates, phase releases);
- It facilitates auditing and traceability through versioning and change management.

Its most profound function can be described as epistemic, insofar as it allows the organisation to distinguish between physiological deviations and anomalous ones, thereby making visible what was previously invisible.

At the same time, the chapter has highlighted that effective standardisation does not necessarily coincide with rigidity. In dynamic contexts, the key lies in distinguishing between a stable core (activities and requirements that guarantee safety, quality, and compliance) and controlled variants (allowing for adaptation to product specifics or operating conditions). This approach prevents processes from being "stifled" and, on the contrary, enables innovation: the standard is understood as the best practice currently known, destined to be superseded by improved solutions. For this reason, standardisation is not a point of arrival but rather a foundation upon which learning cycles can be built, allowing organisations to measure the effects of change, compare alternatives, and institutionalise what proves successful.

The organisational implications are evident. At an individual level, standards accelerate onboarding and upskilling, promote alignment across shifts and teams, and increase operational autonomy by reducing uncertainty. At a process level, they minimise recurring errors and rework, enhance predictability, and simplify handovers between functions (purchasing, warehousing, production, testing, and shipping). From a cultural perspective, they shift the focus from "how it has always been done" to a shared system in which work can be improved by anyone. Finally, in terms of resilience, standardisation serves as insurance against change: it allows processes to be transferred to new facilities or organisational contexts with reduced risk of knowledge loss, disorderly saturation, or inconsistent performance. In summary, the considerations developed in this chapter lead to a clear conclusion: standardisation places the organisation in a position to improve systematically, reducing the friction between planning and execution, and establishing the conditions for continuous improvement to become structural rather than episodic.

The natural transition, therefore, is from the question "how can work be made stable and transparent?" to the question "how can it be improved scientifically and continuously?". The following chapter will address this by presenting the theoretical framework that most effectively integrates these two dimensions: Lean Manufacturing. After clarifying the role of standards as a foundation for stability, the discussion will move on to how they may be embedded within a broader framework of organisational transformation and growth.

CHAPTER 3: Methodology

3.1 An Overview of Lean Manufacturing

Lean Manufacturing is now one of the most influential and widespread paradigms in the field of production and operations management. Although it is often associated with the automotive sector and, in particular, with the Toyota Production System (TPS), Lean is not simply a set of tools, but a managerial philosophy centred on creating value for the customer through the systematic elimination of waste and continuous process improvement. The term lean was introduced and spread globally with the publication of The Machine That Changed the World (Womack, Jones & Roos, 1990), which analysed the performance of the Japanese automotive industry compared to its Western competitors. The study highlighted how Toyota had managed to achieve superior results not so much through massive technological investments, but through a radically different organisation of work, capable of reducing costs, improving quality and increasing production flexibility. The approach, based on reducing non-value-added activities and involving people in decision-making processes, offered a replicable and, above all, culturally transformative model.

In reality, the roots of Lean lie in a much broader journey that began well before the second half of the 20th century. Iuga and Kifor (2013) highlight how the concept of waste elimination and process rationalisation can be traced back to fundamental contributions from the American and European industrial traditions. From Eli Whitney's insights into the interchangeability of parts, to Taylor's studies on standardised work, to Ford's assembly line, it is possible to identify a trajectory that leads directly to the logic of efficiency, quality and continuous flow that characterise Lean. In this sense, the Toyota Production System does not represent a complete break with the past, but rather the evolution and more mature synthesis of existing concepts, reworked and adapted to the Japanese economic and cultural context. The heart of Lean lies in the definition of “value” from the customer's point of view. Anything that does not directly contribute to the creation of value is considered waste (muda) and, as such, must be reduced or eliminated. This logic is accompanied by two other critical dimensions, also inherited from Japanese thinking: mura (irregularity) and muri (overload). The combined reduction of muda, mura and muri is a necessary condition for building stable, flexible production systems capable of adapting to internal and external variability.

Over time, Lean has gradually established itself as a universal approach, transcending the boundaries of the automotive industry to extend to a wide variety of sectors. Sundar et al. (2014)

point out that Lean principles and tools have been successfully adopted not only in traditional manufacturing, but also in sectors such as healthcare, financial services, logistics and even public administration. This process of diffusion has shown that Lean is not tied to a particular type of product or process, but is a cross-cutting methodology that can be adapted to different organisational and cultural contexts.

A central aspect of the literature concerns the distinction between Lean as a philosophy and Lean reduced to a set of tools. Many cases of failed implementation stem from adopting Lean as a "toolbox" to be applied mechanically, without understanding its systemic nature. As both Iuga and Kifor and Sundar et al. observe, Lean tools – from kanban to value stream mapping, from 5S to poka-yoke – only make sense if they are part of a coherent strategic framework, in which the organisational culture truly supports participation, discipline and continuous improvement.

In summary, Lean can be interpreted as a system of thinking and practices that integrates:

1. Strategic objectives, oriented towards creating value for the customer and long-term sustainability;
2. Management principles, which guide the design of processes and interactions between resources;
3. Operational tools, used to put these principles into practice in everyday work.

The aim of this chapter is therefore to provide an overview of the literature on Lean Manufacturing, starting from its historical and conceptual roots, analysing its fundamental principles and main tools of application, and discussing its benefits, limitations and conditions for success. Particular attention will be paid to the link between standardisation and continuous improvement, already introduced in the previous chapter, which in Lean finds a methodological synthesis capable of combining stability and innovation.

3.2 Historical Roots of Lean Manufacturing

Although Lean Manufacturing is most commonly associated with the Toyota Production System (TPS) of the post-war period, its conceptual foundations can be traced back much earlier, to a series of industrial and managerial innovations that emerged in both the United States and Japan. The historical evolution of Lean reflects a gradual convergence of ideas relating to efficiency, quality, process discipline, and worker involvement, culminating in the systemic philosophy recognised today as Lean.

3.2.1 Historical Roots of Lean Manufacturing

The evolution of lean manufacturing, as we have said, cannot be traced back to a single moment of invention, but is the result of a long evolutionary process that combined contributions from both American and Japanese industrial traditions. In the United States, the earliest foundations were laid at the end of the 18th century, when Eli Whitney introduced the concept of interchangeable parts, paving the way for the transition from craft production to large-scale production and reducing dependence on the individual skills of craftsmen. This principle soon became an essential prerequisite for standardisation and mass production. At the beginning of the 20th century, Frederick Winslow Taylor further developed the industrial discipline with his theory of Scientific Management (1911). Through systematic studies of time and methods, Taylor introduced the idea that tasks could be measured, analysed and optimised scientifically, laying the foundations for the concept of standardised work. Although criticised for reducing workers to mere executors, the Taylorist approach, focused on efficiency and process discipline, established itself as a cornerstone of modern production systems. In parallel, Frank and Lillian Gilbreth broadened the perspective by introducing studies on movements and process mapping, also emphasising the importance of ergonomics, worker well-being and the psychological dimensions of motivation. Their focus on reducing unnecessary movements and visualising processes anticipated the lean concepts of waste elimination and operational transparency.

The American evolution culminated in Henry Ford's revolutionary introduction of the assembly line in 1913. Ford's ambition to produce a car accessible to the masses came to fruition with the Model T, assembled in just 93 minutes. His system integrated workers, machines and materials into a coherent flow, drastically reducing production time and costs. The principles of continuous flow, task specialisation and large-scale standardisation led the Ford Motor Company to global success and demonstrated the extraordinary potential of mass production. However, Fordism had obvious limitations: it was an inherently rigid system, optimised for the production of large volumes of uniform goods, but ill-suited to handling variety, market changes or customisation.

It was in post-war Japan that an alternative path took shape, destined to transform and enrich the American legacy, giving rise to Lean Manufacturing. In a context characterised by scarce resources, destroyed infrastructure and the challenge of competing with established Western industries, Japanese manufacturers – and Toyota in particular – developed a model aimed at achieving maximum efficiency with minimum use of resources. Figures such as Kiichiro Toyoda, Eiji Toyoda, Taiichi Ohno and Shigeo Shingo were inspired by the principles of Fordist flow and Taylorist standardisation but reinterpreted them according to Japanese needs and culture. The result was the Toyota Production System (TPS), a model that did not focus on production scale as the ultimate goal, but on flexibility, quality and adaptability. At the heart of the TPS was the systematic elimination of waste (muda) in all its forms: overproduction, waiting times, excess inventory, unnecessary transport, defects, over-processing and failure to utilise people's skills.

Unlike Fordism, which concentrated decision-making power in engineers and managers, TPS assigned responsibility for defining and improving standards directly to workers on the gemba (the place where production takes place). This decentralisation reflected a cultural orientation towards collective responsibility, discipline and continuous learning, transforming workers from mere executors to protagonists of improvement. Another decisive influence came from the quality movement brought to Japan in the 1950s by American scholars such as W. Edwards Deming and Joseph Juran. Deming's Plan-Do-Check-Act (PDCA) cycle and Juran's “quality trilogy” introduced systematic approaches to statistical control, planning and cost reduction, further reinforcing the culture of continuous improvement.

In the 1950s and 1960s, Toyota introduced innovations that definitively distinguished TPS from the Fordist model. The kanban system, a visual scheduling method, made it possible to synchronise production and demand while reducing inventory. Shingo's SMED (Single Minute Exchange of Die) method enabled rapid production changes, increasing flexibility. These innovations, integrated into the Just-in-Time (JIT) philosophy, further reduced waste and improved responsiveness to customer needs. By the 1970s, Toyota had consolidated these practices into a coherent system that combined efficiency, quality assurance and respect for people. Where Fordism thrived on uniformity and economies of scale, TPS demonstrated resilience in contexts characterised by uncertainty, variety and resource constraints.

3.2.2 From Divergence to Convergence

A comparison between American and Japanese contributions highlights two distinct but complementary trajectories. The American tradition was characterised by a focus on productivity, economies of scale and the pursuit of efficiency through standardisation and flow. The innovations of Whitney, Taylor, the Gilbreths and Ford provided the technical and managerial foundations for systematic production control, but they partly neglected flexibility and the cultural and human aspects of work.

The Japanese trajectory, on the other hand, emphasised the elimination of waste, production flexibility and the active involvement of workers. Taking up American innovations, Japan reinterpreted them in an adaptive and participatory way, integrating them into a system focused on widespread quality and continuous improvement. If the Fordist assembly line represented stability and uniformity, TPS embodied resilience, adaptability and constant learning.

Contemporary Lean Manufacturing therefore represents the synthesis of these two traditions. From the American school, it inherits a focus on efficiency and process discipline, while from the Japanese experience it acquires flexibility, a focus on quality and respect for people. The convergence of these approaches has given rise to a comprehensive production philosophy that has transcended the boundaries of the automotive industry and established itself as a universal paradigm for operational excellence. By integrating discipline and adaptability, efficiency and participation, Lean has established itself as a global model capable of addressing the challenges of stability and change in contemporary production systems.

3.2.3 The Concept of Value

The concept of value is the essential starting point for Lean Manufacturing. Unlike traditional production models, which often identify value with quantity produced or internal efficiency, Lean defines it solely from the customer's point of view. From this perspective, only what the customer recognises as valuable and is willing to pay for has value. Everything else, however much time, resources or skills it may absorb, does not generate value and must therefore be reduced or eliminated.

This approach leads to a fundamental distinction between value-added (VA) and non-value-added (NVA) activities. The former are those that contribute directly and measurably to customer satisfaction in terms of product functionality, perceived quality, delivery times or final cost. The latter, on the contrary, do not change the good or service in a way that is appreciable to the customer, even though they require resources and organisational commitment. Operations such as redundant checks, unnecessary handling or waiting times do not increase perceived value and should therefore be considered waste to be eliminated.

However, the definition of value is not limited to the strictly productive level, but is applied on different scales that reflect the progressive extension of the Lean philosophy. At the most operational level, Lean manufacturing concerns individual departments and processes, focusing on the elimination of waste in transformation activities. At a broader level, Lean production considers the entire internal flow of the company, integrating procurement, production and distribution. Lean organisation represents a further step, in which the entire company adopts Lean logic in all its functions, including support and service functions. Finally, Lean enterprise extends Lean principles beyond company boundaries, involving suppliers, partners and customers in a network of shared value creation (figure 8).

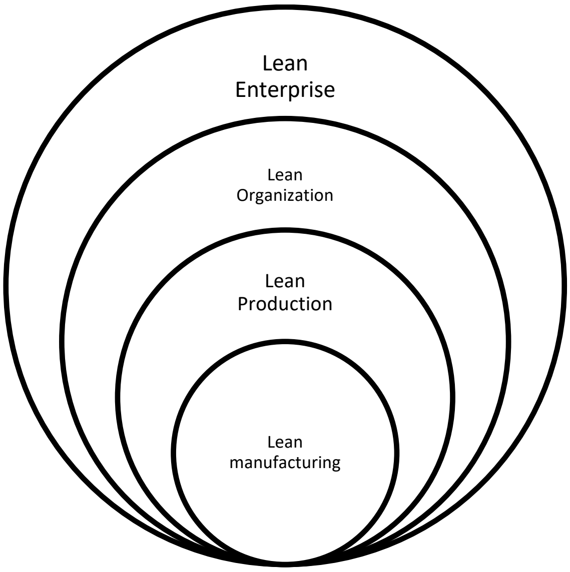


Figure 8:Defining value through steps

In this way, the concept of value does not appear as an isolated criterion, but as the common thread that links all aspects of Lean. At every level, from the production department to the supply chain network, the underlying question remains the same: which activities actually generate benefits for the customer and which ones constitute waste? It is precisely this question that guides every improvement initiative and every strategic decision.

The principle of value, therefore, is not limited to serving as a criterion for analysis: it is the very foundation on which all other Lean principles are based. Without a clear definition of what value means to the customer, it would not be possible to map processes correctly, redesign them coherently, or orient continuous improvement towards truly meaningful goals

3.2.4 Waste and the Three Ms

A fundamental pillar of Lean Manufacturing is the systematic fight against waste, understood not only as visible inefficiencies but also as structural conditions that undermine the creation of value. The Japanese tradition, from which Lean originates, identifies three closely interconnected categories of waste: muda, mura, and muri. Their recognition and control are essential to any path of process optimisation and standardisation.

The term muda refers to activities that do not generate value from the customer's perspective. Toyota classified seven principal types of waste (later extended to eight): overproduction, waiting, unnecessary transport, redundant processing, excessive inventory, unnecessary motion, defects, and the underutilisation of human capabilities. Muda is therefore the most visible manifestation of waste and represents the immediate target of Lean improvement initiatives. In industrial practice, typical examples include maintaining unnecessary inventories that tie up capital, duplicating quality inspections, or experiencing waiting times caused by inadequate scheduling.

Alongside muda, Lean philosophy stresses the importance of addressing two less visible but equally critical phenomena. Mura refers to unevenness and variability in production flows. When market demand is unstable, or when internal processes are poorly balanced, bottlenecks and accumulations of work-in-progress arise, generating systemic inefficiency. A common example is a production line alternating periods of overburden with periods of inactivity, leading to wasted resources and reduced effectiveness.

The third category, muri, concerns the overburdening of people, machines, or systems. This occurs when planning ignores the actual limits of resources, forcing operators to work at unsustainable paces or machines to operate beyond their optimal capacity. The consequences are multiple: declining quality, errors caused by fatigue, more frequent breakdowns, and increased maintenance costs. In this sense, muri is one of the main sources of hidden inefficiency, reducing the long-term resilience of the system.

A crucial point is that the Three Ms are not isolated elements but mutually reinforcing (Figure 9). Irregularity (mura) often leads to overburden (muri), which in turn generates waste (muda). This creates a vicious cycle: unlevelled planning produces peaks of activity, these peaks overstrain resources, and the outcome is an increase in errors, rework, and idle time. It becomes evident that reducing muda cannot be achieved without simultaneously addressing mura and muri.

The Lean literature highlights the central role of process standardisation as a tool for preventing the Three Ms. Establishing clear, shared, and repeatable work methods makes it possible to stabilise flows, reduce variability, and distribute workloads more evenly. Standardisation thus becomes a prerequisite for robust continuous improvement: it not only eliminates visible waste

but also creates the conditions to identify and address the deeper causes of instability and overburden.
In relation to the focus of this thesis, the reference to the Three Ms is particularly significant. The production processes at COBOD, characterised by a high degree of manual work and variability in operating practices, illustrate how mura (irregularity in work methods) and muri (overreliance on individual skills) often represent the root causes of visible waste (muda). Intervening structurally on these dimensions is essential to reduce errors, enhance predictability, and facilitate the transfer of activities into new production environments. Only by addressing the Three Ms in an integrated manner can standardisation translate into systematic and lasting improvement, rather than isolated corrective actions.

3.2.4 The Five Principles of Lean Thinking

Lean Thinking is grounded in five core principles, formulated by Womack and Jones, which provide a methodological framework for transforming traditional production systems into ones capable of generating value with maximum efficiency. These principles are both sequential and cyclical: once completed, the process restarts at a higher level of awareness, thereby supporting continuous improvement.

Defining Value

The starting point of Lean is the definition of value from the customer's perspective. Only by clearly identifying what the customer truly considers useful is it possible to distinguish activities that create value from those that merely consume resources without producing tangible benefits. In this way, organisations can focus their efforts on what is genuinely required, avoiding waste and reducing costs.

Mapping the Value Stream

Once value has been defined, it is necessary to map all activities—from design to delivery—that contribute to the creation of a product or service. Value Stream Mapping enables the identification of activities that add value, those that are necessary but non-value-adding (such as certain controls or logistical steps), and those that are entirely superfluous and should therefore be eliminated.

Creating Flow

The third principle emphasises that value-creating activities must proceed without interruptions, delays, or excessive inventories. This requires reorganising work with a process-oriented perspective rather than a functional one, reducing waiting times and discontinuities. Continuous flow is thus an essential condition for ensuring speed, efficiency, and consistent quality.

Establishing Pull

The "pull" principle ensures that production occurs solely in response to actual demand, whether internal or external. This approach prevents overproduction, reduces stock levels, and mitigates the risk of manufacturing goods that the market does not require. By "pulling" production directly from demand, it also becomes possible to synchronise suppliers, producers, and customers more effectively.

Pursuing Perfection

The cycle of Lean principles concludes with a commitment to continuous improvement (Kaizen). Perfection is understood as an asymptotic goal: it can never be fully attained, yet it must guide organisational decision-making. Through incremental improvements, progress is consolidated and a culture of continuous learning is fostered, where each waste eliminated strengthens the efficiency and resilience of the entire system.

3.3 Kaizen: The Philosophy of Continuous Improvement

In summary, the five principles of Lean Thinking are not isolated rules but interconnected components of a philosophy aimed at creating customer value, systematically reducing waste, time, and costs, while simultaneously reinforcing the organisation's ability to adapt to change.
Kaizen, a Japanese term literally meaning change for the better, has become a cornerstone of modern management philosophy and Lean practice. Popularised in the 1980s by Masaaki Imai, Kaizen emphasises continuous improvement through small, incremental changes rather than radical innovations. This approach reflects the belief that sustainable progress stems from the systematic refinement of everyday activities, involving all members of the organisation – from senior executives to line operators.
Historically, Kaizen finds its roots in post-war Japan, where methods such as statistical process control, introduced by Shewhart and later refined by Deming, laid the foundations for a culture of quality and continuous learning. Toyota subsequently incorporated these ideas into the

Toyota Production System (TPS), making Kaizen one of its central pillars alongside Just in Time (JIT) and Jidoka. The former, JIT, is based on producing only what is required, when it is required, and in the necessary quantity, thereby drastically reducing inventories, waste, and lead times. The latter, Jidoka often referred to as "automation with a human touch", is built on the principle that quality must be ensured within the process itself: whenever an abnormality occurs, production should be halted immediately to prevent the propagation of defects. Together, these three elements Kaizen, JIT, and Jidoka form the backbone of the TPS and, more broadly, Lean Thinking.

The essence of Kaizen can be summarised in three fundamental characteristics. First, it regards improvement as a collective responsibility, rejecting the notion that innovation is the exclusive domain of a few specialists. Second, it highlights the importance of incremental change, showing that even minor adjustments can, over time, deliver substantial gains in quality, productivity, and cost reduction. Third, Kaizen requires process visibility: problems must be directly observed at the gemba (the place where work occurs), analysed transparently, and resolved systematically.

Beyond its manufacturing origins, Kaizen has gradually spread to a variety of sectors, including healthcare, IT, and services. In these contexts, it has proven effective in standardising processes, enhancing customer value, and fostering a culture of learning. While the benefits of Kaizen may not always be reflected in immediate financial returns, organisations that adopt it report long-term improvements in efficiency, employee engagement, and resilience.

In summary, Kaizen represents far more than a methodology: it is a management philosophy and an organisational mindset. By embedding continuous improvement into everyday practice, and combining it with the principles of Just in Time and Jidoka, organisations are able to reduce waste, ensure quality at the source, empower people, and promote sustainable growth in dynamic environments.

In order to move from Kaizen as a philosophy to Kaizen as a practical approach, a variety of tools have been developed to guide improvement efforts. Among the most widely applied are Poka-Yoke, which prevents or immediately detects errors within processes, and the PDCA cycle, a structured method for implementing and sustaining continuous improvement.

3.3.1 Poka-Yoke

The concept of Poka-Yoke, developed by Shigeo Shingo in the 1960s within the Toyota Production System, refers to the design of processes and devices that either prevent errors from occurring or make them immediately visible at the moment they arise. Literally translated as "avoiding inadvertent mistakes", Poka-Yoke is based on the principle of embedding quality directly into the process, rather than relying exclusively on inspections carried out after production.

Traditionally, Poka-Yoke has been widely applied in manufacturing contexts through physical or procedural safeguards: components designed to be assembled in only one correct orientation, sensors that stop machines when anomalies are detected, or visual signals that alert operators to a missing step. These mechanisms can be classified into two main categories: preventive devices, which eliminate the very possibility of an error occurring, and detective devices, which identify mistakes at their source before they propagate along the value stream.

Recent studies have shown that Poka-Yoke can be applied beyond conventional assembly contexts. Tommelein (2008) highlights its relevance in the construction sector, where variability in tasks and environments makes traditional quality control insufficient. In this field, error-proofing entails redesigning workflows, interfaces, and equipment in order to minimise human error in dynamic and uncertain operating conditions. Similarly, Zhang (2014) extends the application of Poka-Yoke to the design of information systems, emphasising that error-proofing mechanisms are equally essential for ensuring reliability and robustness in data-driven processes. These contributions illustrate how Poka-Yoke has evolved from a tool primarily used in assembly operations to a broader philosophy of error prevention applicable to both manufacturing and service contexts.

From an organisational perspective, Poka-Yoke offers several advantages: it supports standardisation, reduces dependence on constant operator vigilance, increases reliability, and enhances safety. For companies such as COBOD, where production processes are still characterised by high levels of manual work and variability, Poka-Yoke represents a particularly effective strategy to stabilise operations, reduce rework, and ensure process repeatability.

3.3.2 PDCA: The Continuous Improvement Cycle

The Plan–Do–Check–Act (PDCA) cycle, also known as the Deming or Shewhart cycle, is a structured methodology for continuous improvement that provides organisations with a systematic approach to problem-solving and learning. Originating in the work of Walter Shewhart in the 1930s and subsequently refined and popularised by W. Edwards Deming, PDCA embodies the principle that improvement is not a one-off intervention but rather an iterative process of experimentation and refinement.

The cycle is composed of four distinct but interdependent phases:

1. Plan: identify a problem or opportunity, gather data, and design a countermeasure or improvement strategy. This stage emphasises a clear understanding of the current state and the establishment of measurable objectives.
2. Do: implement the proposed change on a small scale, testing its feasibility in a controlled setting.
3. Check: evaluate the results by comparing actual outcomes with expected objectives, using both quantitative and qualitative data. This phase provides evidence of whether the intervention has produced the intended effects.
4. Act: standardise and integrate successful improvements into routine processes, or revise the plan and repeat the cycle if the desired results have not been achieved.

One of the main strengths of PDCA lies in its ability to reduce the risks associated with large-scale organisational change. By promoting incremental learning through small-scale testing, PDCA creates an environment in which mistakes can be detected early and corrected, thereby avoiding costly failures. As highlighted by Taylor et al. (2013), the effectiveness of PDCA is closely tied to how rigorously each phase is executed: superficial or incomplete application often leads to limited or unsustainable results. This underscores the importance of a disciplined and evidence-based approach.

PDCA is also closely connected with Kaizen, since both rest on the idea that improvement must be continuous, participatory, and grounded in observable facts. When integrated with Lean tools such as Standard Work and Poka-Yoke, the PDCA cycle becomes a powerful driver of operational excellence, allowing organisations to stabilise processes, reduce variability, and institutionalise learning.

CHAPTER 4: Current State Analysis

4.1 The Company: History, Mission, and Competitive Positioning

COBOD International is a Danish company founded in 2017 as a spin-off of 3D Printhuset, a firm that had been experimenting with the applications of 3D printing in the construction sector since 2015. The pioneering BOD1 project, which in 2017 led to the construction of the first 3D-printed house in Europe, located in Copenhagen, represented a turning point: from that experience emerged the ambition to develop large-scale machines specifically designed for construction, with the aim of transferring the principles of additive manufacturing to a sector traditionally characterised by slowness, fragmentation, and limited automation. The success of this pioneering project is exemplified in the interiors of one of the first 3D-printed houses (Figure 9), which demonstrate how additive manufacturing can deliver both structural solidity and high standards of liveability.

Figure 9:Printed House

From 2019 onwards, with the launch of the BOD2, COBOD established itself as an international technological leader. Thanks to its modular and scalable architecture, the BOD2 has been adopted in numerous projects across Europe, North America, the Middle East, and Asia, marking the transition from an experimental phase to large-scale commercialisation. In the following years, the expansion of the product line with the BOD3 and the BOD XL enabled the company to address more complex demands, further consolidating its reputation.
From an organisational perspective, COBOD maintains its headquarters in Copenhagen, where research and development, production, and management are concentrated. In recent years, the company has also opened regional offices and hubs in North America and the Middle East, with the aim of providing local support to customers and partners. Despite its global reach, COBOD retains a relatively lean structure, typical of start-up organisations: strategic decisions are taken centrally in Denmark, while international collaboration is fostered through a network of distributors and service providers.

The company's economic growth reflects both the expansion of the Construction 3D Printing (C3DP) market and COBOD's ability to position itself as a key player within it. From the first prototypes sold to research institutions and pioneering builders, the firm has progressed to managing projects with global partners such as General Electric Renewable Energy, PERI Group, and Holcim. These collaborations have contributed to strengthening financial stability and increasing international visibility. In just a few years, COBOD has transformed an experimental initiative into a structured business, capable of attracting investment and generating consistent growth in terms of revenue, orders, and global presence.

The company's mission is unambiguous: to revolutionise the construction sector through the digitalisation and automation of processes, thereby reducing time, cost, and environmental impact. Its strategic goal is to guide the construction industry in the transition towards a leaner, more efficient, and sustainable model, consistent with the principles of Lean Manufacturing and aligned with global sustainability challenges.

4.2 The Technologies Developed: 3D Construction Printing and the Evolution of BOD Printers

COBOD's technology belongs to the sector of 3D construction printing (C3DP), a rapidly expanding field that is progressively redefining traditional building practices. The underlying principle is based on the extrusion of cementitious materials through large gantry systems, controlled by software that converts digital models into machine instructions. This process enables the production of complex geometries with a high degree of precision, while drastically reducing the need for formwork, intermediate phases, and labour-intensive practices typical of conventional construction.

A distinctive feature of COBOD's printers is their modular architecture, which makes them adaptable to projects of varying scale. In particular, the BOD2 can be configured with a variable number of modules, ranging from four to ten legs, depending on the dimensions and specific requirements of the project, an example of this modular configuration can be observed in Figure 10.

This flexibility allows the printer to cover highly diverse operational areas, from small residential buildings to large commercial or infrastructural projects. Such versatility has become one of the company's main competitive strengths, enabling it to deploy its technology across a wide range of international contexts.

The evolution of COBOD's portfolio illustrates a trajectory of constant innovation.

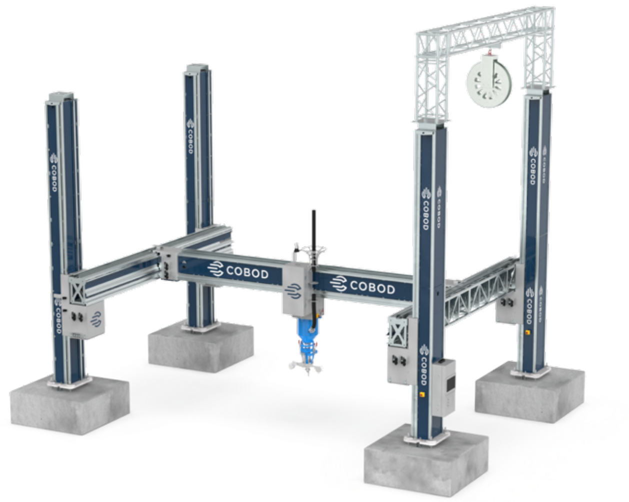


Figure 10:BOD2 printer in a four-leg configuration (Source: Company photo archive, internal data)

The pioneering BOD1, used to construct the first 3D-printed house in Europe, laid the foundations for the BOD2 (2019), which marked the transition to international commercialisation. The BOD2 quickly became the most widely adopted 3D construction printer worldwide, recognised for its scalability, reliability, and compliance with industry standards.

More recently, the product line has expanded with the BOD3, designed to increase productivity and support larger projects. As shown in Figure 11, the BOD3 is characterised by a lighter structural configuration compared to previous models, with a reduced number of supporting columns ('legs'), making the system more compact while retaining its modular adaptability.

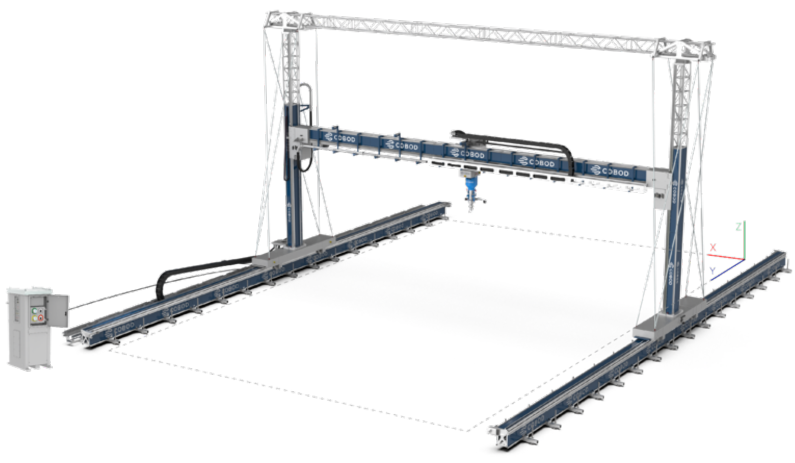


Figure 11:The BOD3 construction printer (Source: Company photo archive, internal data)

The portfolio was further extended with the BOD XL, described as the world's largest 3D construction printer. In 2024, two BOD XL units were installed in Doha, Qatar, to build a multi-thousand-square-metre school commissioned by the Public Works Authority "Ashghal". This project represents the largest 3D-printed structure ever realised, providing evidence that additive technology has now achieved an unprecedented industrial scale. An example of the BOD XL is shown in Figure 12.

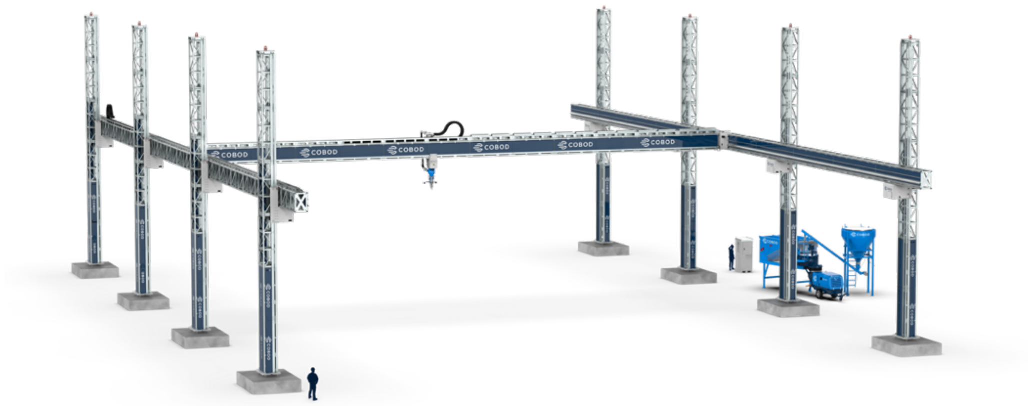


Figure 12:BOD XL (Source: Company photo archive, internal data)

At the core of COBOD's approach lies the use of real concrete as the primary construction material. Concrete remains the most widely used material in the building sector due to its high compressive strength, durability, and long service life properties that make it suitable for high-rise buildings, bridges, and infrastructures requiring structural integrity. It is also highly versatile, as it can be moulded into diverse shapes and sizes, thereby enhancing architectural freedom. From a sustainability perspective, concrete offers a relatively contained carbon footprint over its lifecycle, especially when produced with supplementary cementitious materials, and provides excellent insulating and fire-resistant properties.

A further step forward has been made through COBOD's partnership with CEMEX, which led to the development of the D.fab solution. This system enables the use of locally sourced concrete, reducing costs by 80–90% compared with dry-mix mortars, adapting to climatic conditions, and improving sustainability by lowering cement content and incorporating recycled aggregates (Figure 13).

Through this combination of technological scalability and material innovation, COBOD has transformed 3D construction printing from an experimental solution into an industrially viable technology, consolidating its role as a global leader in the digital transformation of the construction sector.

Figure 13:Ongoing BOD2 projects Source: (Cobod, 2025, available at https://www.companyname.com)

4.2.1 Modularity and Scalability of the Technology

Modularity represents the fundamental technical principle of COBOD's printers and constitutes the cornerstone of their scalability. Each machine is conceived as a composable system, in which structural modules can be added or removed according to the dimensions of the project. In particular, the BOD2 can be configured with a variable number of legs, ranging from four to ten, with extensions along the axes that allow the printer to adapt to projects of very different scales, from small residential houses to large public buildings and infrastructures.

Scalability, which is closely linked to modularity, enables users to start with "basic" configurations for small-scale projects and progressively expand the system by adding standardised modules. In this way, COBOD printers are not static machines but flexible systems capable of growing alongside production and market needs. From an operational perspective, this logic reduces initial investment costs, optimises assembly and disassembly times on site, and allows for a more efficient use of resources.

The technological evolution of the product line confirms this approach. With the BOD3, COBOD introduced further innovations: the system can include extended rails along the Y-axis, which enable coverage of even larger surfaces, and a robotic arm add-on, designed to expand the range of applications and enhance process automation. These developments reinforce the modular concept, making the printer even more versatile and suitable for industrial-scale projects.

Among the different machines developed by COBOD, the BOD 2 serves as the exemplary case for concretely illustrating the concept of modularity and scalability. For this reason, its main technical specifications are reported below (Table 2), as they demonstrate how the modular architecture is translated into real operational performance.

Table 2:BOD2 Technical Specifications (Source: COBOD, 2025, available at www.cobod.com)

PARAMETER	VALUE
Operating weight	~5,390 kg
Leg configuration	4 – 10 (modular)
Maximum print width	14.6 m
Maximum print height	8.1 m (plus concrete base)
Layer thickness	5 – 40 mm
Layer width	30 – 300 mm
Axis speed (X/Y)	up to 250 mm/s
Material output	up to 7.2 m^3/h
Maximum aggregate size	10 mm
Power supply	380–480 V (three-phase + N + PE)
Setup time	4 – 6 hours
Dismantling time	2 – 3 hours
Personnel required	3 – 4 operators

These data highlight that modularity and scalability are not merely engineering concepts but determinants of operational efficiency. The ability to transport the printer in modules, assemble it quickly, and reconfigure it according to project requirements drastically reduces downtime, increases process resilience, and enables the application of the technology in construction sites characterised by spatial or operational constraints.

In this sense, the BOD product line, and particularly the BOD2, constitutes a paradigmatic example of how 3D construction printing is evolving towards scalable, automated systems aligned with the principles of Lean Manufacturing.

4.3 Manufacturing Model and Material Management

At COBOD, production follows a produce-to-order model aligned with the Lean pull principle: each unit is built only after order confirmation and deposit, which limits inventory and lets the team tailor size, modular configuration, and options. The product itself is a large gantry system built on modular trusses along the Z (vertical) and Y (longitudinal) axes, with an X-truss spanning across; motion is executed by four key subassemblies ("carriages"): the Z-Carriages travel on the vertical trusses, the Y-Carriages run along the Y-trusses, the X-Carriage carries the printhead on the X-axis, and the E-Box houses drives/electronics and power distribution (Figure 14).

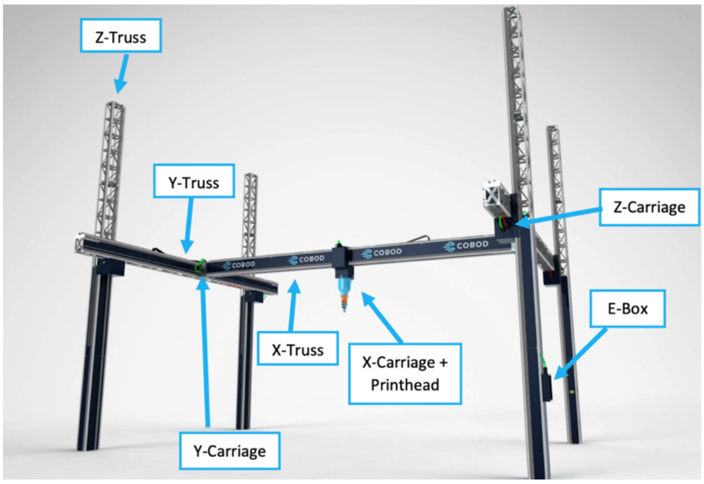


Figure 14:BOD 2 structure (Source:Company photo archive, internal data)

Most of the components arrive through local carriers in small vans and are simply dropped at a designated spot near the plant's main gate, with paperwork left in the office. Inside the building, storage conditions such as temperature and humidity are controlled, ensuring the safe handling of sensitive parts. However, space constraints mean that the largest elements, the trusses, are often stored outside in front of the facility. This practice exposes them to weather and salty air from the Copenhagen–Malmö port, which can accelerate corrosion and represents a clear quality risk.

Trusses arrive pre-finished from suppliers (cut, painted, and fitted with rack teeth), while cable harnesses and e-chains are delivered pre-assembled to route power and signal safely across moving axes; motors, gears, and electronic drivers come from specialized vendors.

Because of this architecture, COBOD's manufacturing is primarily assembly work, integrating ready components into a coherent motion system rather than transforming raw materials. Once an order drops, procurement prioritizes long-lead items (carriages and critical modules can exceed ten weeks) while pulling stocked consumables; the end-to-end flow then proceeds through different steps:

1. mechanical assembly,
2. electrical assembly (installing harnesses and controls into the carriages),
3. commissioning (alignment, calibration, dry runs)
4. shipping

Safety elements such as end-stops and finger guards, together with laser alignment and structured checklists, complete the technical setup and ensure the printer is both accurate and serviceable.

4.3.1 Mechanical Assembly

The mechanical assembly stage involves fitting the major components of the printer into the carriages, installing motors, and sealing external parts to make the machine suitable for outdoor operation. This area of production is relatively well organized, supported by a team that applies Lean practices such as 5S on a daily basis. However, planning is not always systematic: weekly tasks are often defined in real time depending on part availability and production priorities, which can reduce efficiency and predictability.

4.3.2 Electrical Assembly

Electrical assembly begins with the preparation of cable harnesses in the dedicated electrical workshop. These harnesses are then transferred to the production line, where they are integrated into the carriages. Once installed, technicians perform functional checks to verify proper wiring and ensure that no short circuits or irregularities are present. This step is critical to guarantee safe and consistent printer performance before moving on to final assembly.

4.3.3 Commissioning

The commissioning phase is where the printer is fully assembled, aligned, and tested for the first time as a complete system. The process starts with the installation of the Z-Carriages on the vertical trusses, followed by the positioning of the support legs using laser alignment tools. The Y-Trusses are then mounted, and the Printhead together with the Y-Carriages is installed on the X-axis. Due to the size and weight of the components, at least two operators and the use of a crane are required to complete this step safely. Protective devices such as end-stops and finger guards are added, and the e-chains carrying the electrical cabling are installed along the trusses to connect all carriages.

Once assembled, the printer undergoes dry run tests, during which it is connected to the control software, calibrated, and subjected to repeated movement cycles. This ensures that all axes move as expected and that no anomalies, such as delays or vibrations, are present. Any issue detected must be addressed immediately, sometimes requiring partial disassembly to resolve.

The final activity within commissioning is the customer demonstration. At this stage, the printer is connected to the material handling system and used to perform sample prints, typically simple shapes or logos so that the client can directly verify machine performance. The demo usually lasts several hours and involves multiple operators to manage both the printer and the material flow. Once the demonstration is successfully completed and the customer is satisfied, the equipment is approved for shipment.

4.3.4 Testing

Once testing is complete, the printer is disassembled and prepared for shipment. Large open-top 40-foot containers are used for the main modules, while smaller 20-foot containers may carry accessories or additive materials. Trusses are lifted into the containers with a crane, stacked with wooden spacers to prevent damage, and secured with straps. Alongside the main equipment, additional kits requested by the customer as maintenance tools are included. A recurring challenge is the coordination of container arrivals: delays are common, which often forces completed printers to remain in the facility and extends the overall lead time. Furthermore, the need to bring containers physically inside the plant for loading requires clearing and cleaning space, which negatively impacts efficiency

4.3.5 Visual representation of the production flow

To provide a clear and immediate overview of how the production department works, a flow chart has been created that outlines the main stages of the process (Appendix A). The entire flow is divided into key steps :

- Documentation
- Mechanics
- Electronics
- Assembly
- Commissioning
- Testing
- Shipping and Debugging (which represent the backbone of daily activities).

The work takes shape as soon as the components arrive: on the one hand, the mechanical team, which deals with the the carriages and structural parts, and on the other, the electrical team, which handles cable harnesses, control boxes, and command systems. The two lines of work come together when the carriages, already mechanically assembled, are completed with the integration of wiring and functional elements. From here, the product moves on to the final stages: commissioning, where it is assembled and calibrated as a system, then tested and finally prepared for shipment.

From the perspective of human resources, the electrical department currently consists of only two operators whereas in the past it was larger, which makes the workflow highly dependent on their skills. The mechanical department, on the other hand, has about five employees, although not all of them are always present, as they are often involved in providing technical support for printers installed abroad. When necessary, however, there is no lack of collaboration: colleagues from other departments are also involved to ensure continuity of operations.

The flow chart in the appendix is therefore not only descriptive: it allows you to see briefly how the work moves, where the departments intersect and where the main activities are concentrated. It is a useful step in introducing the analysis of critical issues, which will be explored in more detail in the following paragraphs.

4.4 Variability of production processes

To analyse how stable or variable the production processes are, data collected with Clockify, the time tracking system implemented at COBOD in 2020, was used. At first, monitoring was rather limited: only the assembly times for the trolleys were recorded, and only the "hands-on" time, i.e. the time during which the operator was physically working on the component. Over the years, however, the system has been expanded to include all stages of production, from preparation work to the complete construction of the printer.

This expansion has provided a broader and more detailed database, albeit not a perfect one. The data collected depends on the operators, who must independently record the hours worked: a method that inevitably leads to differences in the level of precision, consistency and accuracy. Despite these limitations, it is the most comprehensive source available today and has therefore been taken as a reference for the study.

The sample analysed includes 31 BOD2 printers with similar configurations, so that the data is comparable. For each printer, the times for the main production tasks were taken into account: Documentation → Mechanics → Electronics → Assembly →Quality control →Commissioning → Customer demo →Shipping and Debugging.

Initial analysis of raw data

Three statistical indices were calculated for each phase: mean (AVG), standard deviation (ST.DEV) and coefficient of variation (CV%), which measures the relative dispersion of values with respect to the mean. In simple terms, the higher the CV%, the greater the variability of the times.

The initial results, obtained without any correction, are shown in Table 3.

Table 3:Raw data (mean, standard deviation, CV%)

TASK	AVG (H)	ST. DEV (H)	CV %
Documentation	4,736	2,352	50%
Xyz Carriages Mechanics	56,965	12,345	22%
Xyz Carriages Electronics	90,255	36,131	40%
Assembly of further parts	7,222	8,988	124%
Quality Control	5,461	5,563	102%
Commissioning	71,297	26,411	37%
Customer Demo	3,328	1,468	44%
Shipping	66,570	24,310	37%
Debugging	2,952	4,153	141%

The table immediately shows that the longest phases are electrical assembly (approximately 90 hours on average) and commissioning (71 hours). However, the most interesting data is the significant irregularity of certain activities: for example, the assembly of further parts and debugging have a CV of over 120%, which means that the times vary greatly from one printer to another. Even Quality Control, which should be a fairly standard phase, shows a variability of over 100%.

These figures confirm the impressions gathered directly in the field: the processes do not follow clear standards, and the duration of the activities depends greatly on the operating conditions and the skills of those performing them.

Data cleaning: outlier management

To make the analysis more robust, it was decided to eliminate values considered anomalous. This was done by calculating the Z-score, which indicates how much a data point deviates from the mean in terms of standard deviations. Values with $|z| > 2$ were excluded, i.e. those too far from the mean to be considered representative.

The choice of this threshold is justified by the fact that, in a normal distribution, over 95% of the data lies within two standard deviations. In other words, the excluded values were effectively "off scale" and risked distorting the conclusions.

Analysis of corrected data

After cleaning the outliers, the mean, standard deviation and CV% were recalculated. The new results are shown in Table 4.

Table 4:Corrected data (mean, standard deviation, CV%)

TASK	AVG(H)	ST.DEV(H)	CV%
Documentation	4,394	1,403	32%
Xyz Carriages Mechanics	56,965	12,345	22%
Xyz Carriages Electronics	90,255	36,131	40%
Assembly of further parts	5,464	6,068	111%
Quality Control	4,750	2,941	62%
Commissioning	68,158	16,048	24%
Customer Demo	3,558	1,210	34%
Shipping	64,861	22,753	35%
Debugging	2,113	2,554	121%

Even after removing the outliers, the situation does not change substantially: the Assembly of further parts and Debugging phases remain highly variable, with CVs above 100%. Quality control settles at around 62%, which is still high for a phase that should have much more predictable times.

The only relatively stable activities are mechanical (CV 22%) and commissioning (24%), although even these cannot be said to be fully under control.

Graphical representation

To make the results easier to read, the mean values and standard deviations have been represented graphically in Appendix B.

The visual comparison confirms what is highlighted in the tables: the critical issues are not due to a few anomalous values, but reflect a structural condition of the production process.

Conclusions on the analysis

This analysis shows that variability is not a problem limited to a few cases, but a structural feature of the production process. The high degree of manual labour, dependence on individual skills and lack of standard procedures mean that processing times are difficult to predict and vary greatly from one machine to another. High manual labour generates low value-added activities and rework, which in Lean thinking are considered Muda (waste). As Imai (1986) points out with the Kaizen approach, the absence of operating standards increases the likelihood of errors and raises indirect costs.

It is true that the data comes from an imperfect system such as Clockify, which is based on self-reporting and is therefore not always consistent. However, the fact that the results remain similar even after removing outliers shows that the problem is not solely dependent on the quality of the data collection: it reflects the reality of the process.

In other words, current production is unstable and poorly standardised. This complicates planning, slows down efficiency and increases the risk of delays. For this very reason, process standardisation is a strategic priority and will be addressed in the following sections as a key lever for reducing variability and improving overall performance.

All spreadsheets and detailed processing steps are provided in Appendix B.

4.5 Value Stream Map, Current State (BOD2)

The literature on production process improvement clearly shows that the Value Stream Map (VSM) is one of the most effective tools for representing and understanding how a flow works. This diagram makes it possible to visualise all the stages of work, distinguish between activities that generate value and those that involve waiting, reworking or waste, and immediately identify bottlenecks.

Applying this approach to the BOD2 case, I have constructed a map that summarises the path of materials and information within the production process.

Map structure and groupings

To make the VSM clearer and more realistic, I chose to group some phases together:

- the Assembly of further parts activities were divided between the mechanical and electronic parts, where they are actually carried out;
- Debugging and Customer demo were combined with Commissioning, because in practice they take place at the same time, when the machine is started up and tested;
- Documentation has been included in the Shipping phase, as manuals and paperwork travel with the printer.

Ultimately, the main flow is therefore:

Unloading → Mechanics → Electronics → Quality Control → Commissioning (with Debugging and Demo) → Shipping (with Documentation).

The SQDC datasheets

Under each phase, I have included a small diagram that follows the SQDC logic (Safety, Quality, Delivery, Cost).

- Safety summarises the main safety risks.
- Quality indicates how stable or variable the phase is (using the coefficient of variation CV%).
- Delivery shows the average time required.
- Cost highlights in a qualitative way how much that phase weighs in terms of resources or waste.

These datasheets are used to provide an immediate overview of the strengths and weaknesses of each block.

Production phases

- Unloading components from the warehouse takes approximately 30 hours. It is a low-risk activity with low costs, but it is highly sensitive to the availability of parts and the accuracy of the ERP: a single error in the warehouse is enough to slow down the entire flow.
- Mechanical Assembly takes an average of 60 hours, with limited variability (CV 22%). This is manual work carried out by around five operators, although they are not always all available because they are often also involved in providing technical support to existing customers.
- Electronics, this is the longest phase (93 hours) and one of the most variable (CV 40%). It requires wiring, control box and camera assembly, delicate tasks that depend on very

specific skills. Only two people work here, which makes this phase the real bottleneck of the process.

- Quality Control lasts about 5 hours, but with high variability (CV 62%). This means that checks do not always run smoothly: defects often emerge that require reworking, resulting in increased time and costs.
- Commissioning + Debugging + Demo, this is the phase in which the printer is started up, calibrated and tested in front of the customer. On average, it lasts 74 hours and is very critical, because this is where most of the problems to be corrected are concentrated. The operational risk is higher, costs increase if something goes wrong, and variability remains significant.
- Shipping + Documentation, packing, paperwork and shipping take about 69 hours. It is a low-risk logistics activity, but one that is strongly influenced by ERP and the alignment between data and inventory.

The time ladder and production lead time

Adding up all the stages, we obtain a production time of approximately 331.5 hours (including unloading). This is equivalent to 41.5 working days of 8 hours each, or approximately 8 weeks and 1 day, considering a 5-day week.

However, not all of these hours are valuable: most (~85%) represent activities that actually transform the printer (Value Added), while the rest is time lost in rework, non-standard checks or waiting (Non Value Added). The areas that generate the most NVA are Quality Control, Debugging and part of Electronics, where high variability leads to delays and inefficiencies.

Key Insights

The VSM highlights three crucial aspects:

- bottlenecks (Electronics and Commissioning),
- phases with high variability (Quality Control and Debugging),
- dependence on individual skills (only two operators in Electronics).

These elements explain why the overall Production Lead Time is so high and unstable. In addition to describing the current situation, the map also provides the basis for imagining a more streamlined Future State, in which reducing variability and rework becomes the priority.

The complete Value Stream Map, with a graphical representation of the flow and the SQDC datasheets for each phase, is provided in Figure 15.

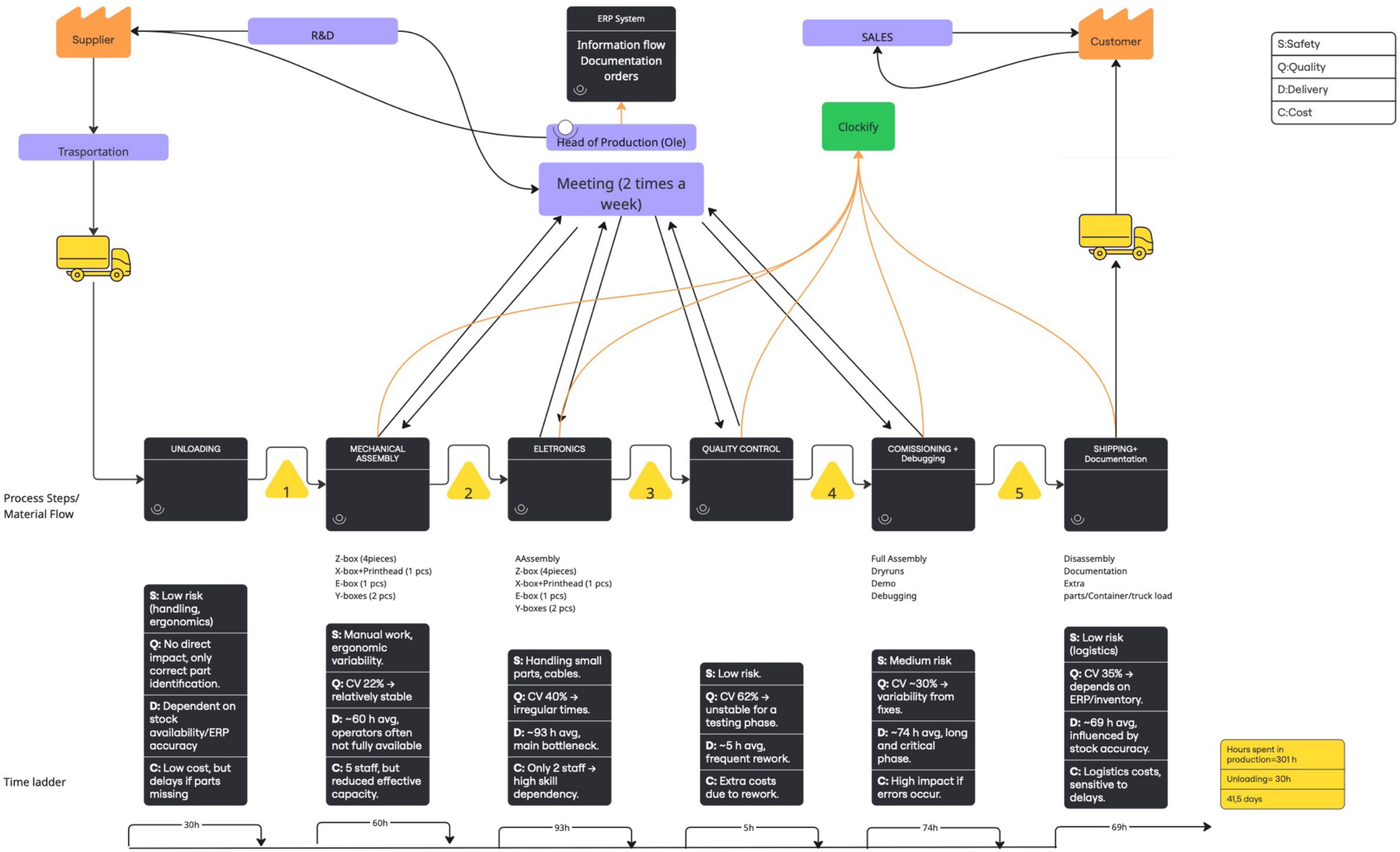


Figure 15: Current Value Stream map

4.6 The Use of the Company ERP

The company relies on Microsoft Dynamics Business Central (Figure 16) as its ERP platform. During my time in the company, I had the opportunity to explore and analyze how this system is actually used across different departments. One of the first things that became evident was that only a few people are truly able to use it effectively. This creates a series of issues: many employees are not fully independent in entering or managing data and therefore have to rely on more experienced colleagues. As a result, valuable time is lost and, in some cases, mistakes occur, especially when communication is not direct or well structured. This difficulty demonstrates how ERP is still unable to fully perform its role of information integration. In the literature, the digitisation of production processes (digital lean) is seen as a key tool for reducing errors, synchronising departments and improving data traceability (Buer et al., 2018).

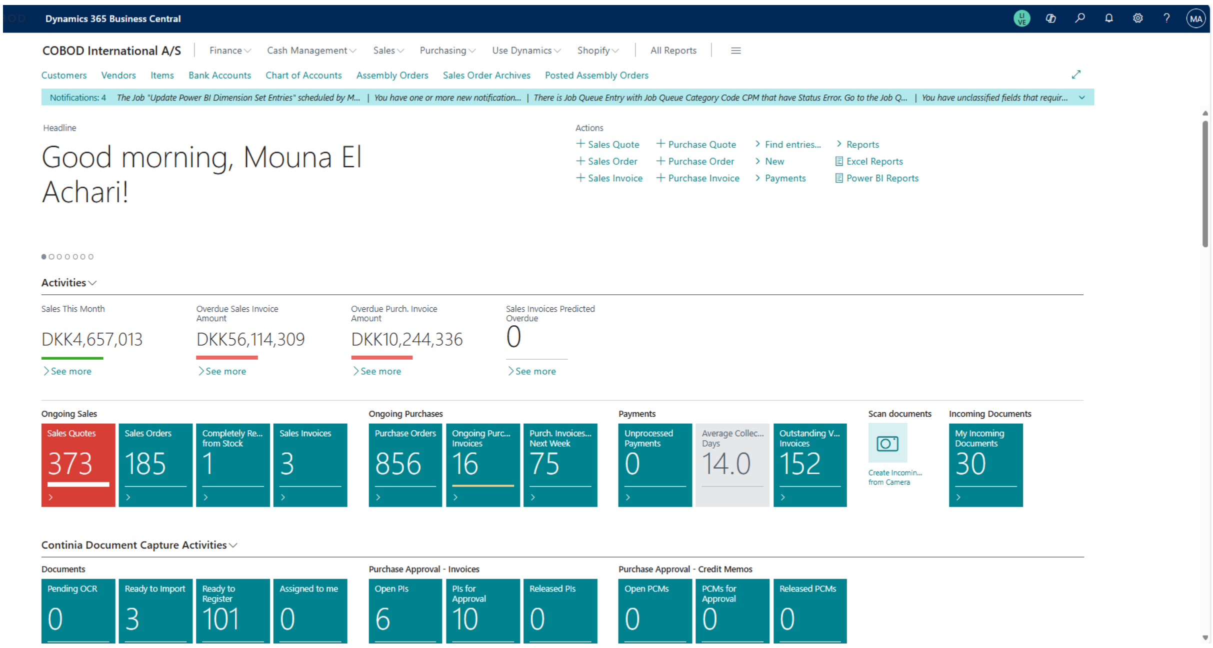


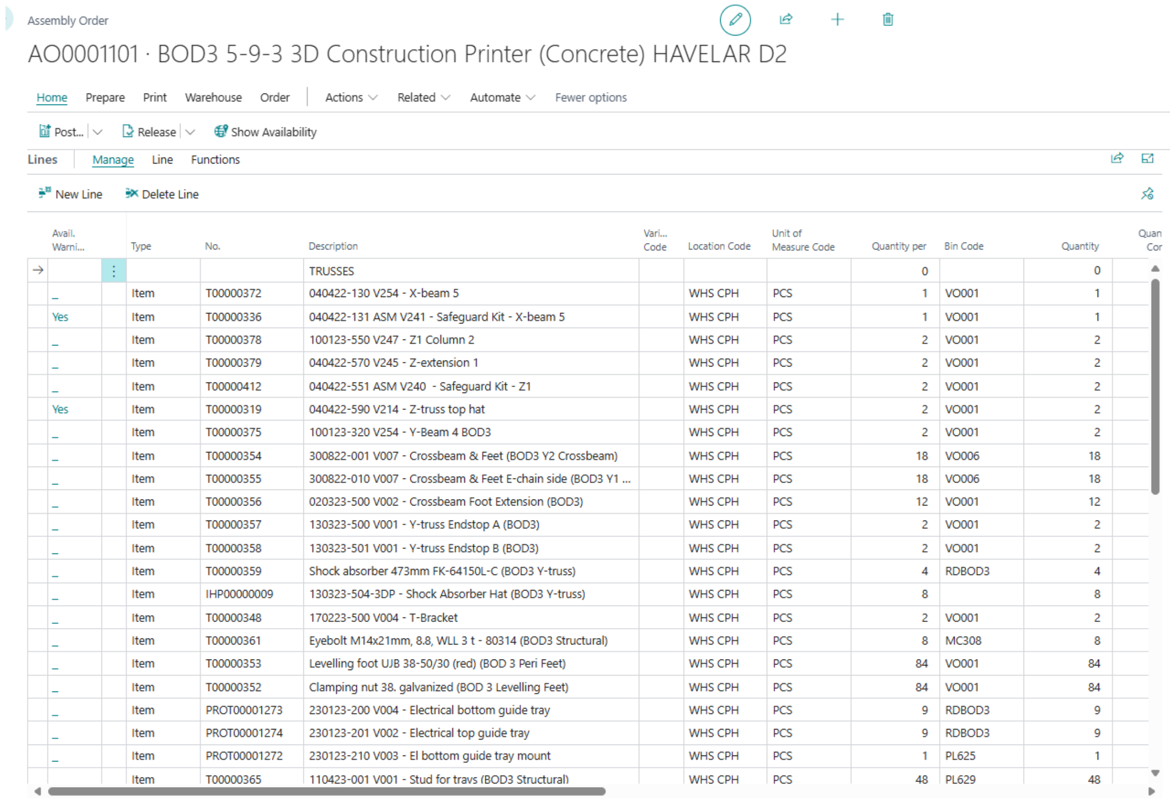
Figure 16: Company ERP portal

In general, the sales department is responsible for creating customer orders, while the production

department handles purchases from suppliers. However, one of the main difficulties encountered relates to the management of assembled orders in the ERP system.

To explain this more clearly: a BOD2 printer consists of hundreds of parts, many of which are not single components but assemblies made up of multiple sub-components (Figure 17). This means that, whenever a printer is sold, it is necessary to build in the ERP the entire bill of materials (BOM) that describes the product’s structure. In theory, this should be a straightforward process, but in practice it proves to be complex for two main reasons:

- not everyone has a deep knowledge of the technical composition of the printer, and there is no standardized documentation that can guide the creation of the BOM step by step;
- the possible configurations of the printer can vary considerably, making the process even more complicated.



Avail. Warni...	Type	No.	Description	Vari... Code	Location Code	Unit of Measure Code	Quantity per	Bin Code	Quantity
			TRUSSES				0		0
_	Item	T00000372	040422-130 V254 - X-beam 5		WHS CPH	PCS	1	VO001	1
Yes	Item	T00000336	040422-131 ASM V241 - Safeguard Kit - X-beam 5		WHS CPH	PCS	1	VO001	1
_	Item	T00000378	100123-550 V247 - Z1 Column 2		WHS CPH	PCS	2	VO001	2
_	Item	T00000379	040422-570 V245 - Z-extension 1		WHS CPH	PCS	2	VO001	2
_	Item	T00000412	040422-551 ASM V240 - Safeguard Kit - Z1		WHS CPH	PCS	2	VO001	2
Yes	Item	T00000319	040422-590 V214 - Z-truss top hat		WHS CPH	PCS	2	VO001	2
_	Item	T00000375	100123-320 V254 - Y-Beam 4 BOD3		WHS CPH	PCS	2	VO001	2
_	Item	T00000354	300822-001 V007 - Crossbeam & Feet (BOD3 Y2 Crossbeam)		WHS CPH	PCS	18	VO006	18
_	Item	T00000355	300822-010 V007 - Crossbeam & Feet E-chain side (BOD3 Y1 ...		WHS CPH	PCS	18	VO006	18
_	Item	T00000356	020323-500 V002 - Crossbeam Foot Extension (BOD3)		WHS CPH	PCS	12	VO001	12
_	Item	T00000357	130323-500 V001 - Y-truss Endstop A (BOD3)		WHS CPH	PCS	2	VO001	2
_	Item	T00000358	130323-501 V001 - Y-truss Endstop B (BOD3)		WHS CPH	PCS	2	VO001	2
_	Item	T00000359	Shock absorber 473mm FK-64150L-C (BOD3 Y-truss)		WHS CPH	PCS	4	RDBOD3	4
_	Item	IHP00000009	130323-504-3DP - Shock Absorber Hat (BOD3 Y-truss)		WHS CPH	PCS	8		8
_	Item	T00000348	170223-500 V004 - T-Bracket		WHS CPH	PCS	2	VO001	2
_	Item	T00000361	Eyebolt M14x21mm, 8.8, WLL 3 t - 80314 (BOD3 Structural)		WHS CPH	PCS	8	MC308	8
_	Item	T00000353	Levelling foot UJB 38-50/30 (red) (BOD 3 Peri Feet)		WHS CPH	PCS	84	VO001	84
_	Item	T00000352	Clamping nut 38. galvanized (BOD 3 Levelling Feet)		WHS CPH	PCS	84	VO001	84
_	Item	PROT00001273	230123-200 V004 - Electrical bottom guide tray		WHS CPH	PCS	9	RDBOD3	9
_	Item	PROT00001274	230123-201 V002 - Electrical top guide tray		WHS CPH	PCS	9	RDBOD3	9
_	Item	PROT00001272	230123-210 V003 - El bottom guide tray mount		WHS CPH	PCS	1	PL625	1
	Item	T00000365	110423-001 V001 - Stud for travs (BOD3 Structural)		WHS CPH	PCS	48	PL629	48

Figure 17:Assembly order for a BOD3

As a result, the BOM is not always built correctly. This lack of standardization not only increases the risk of mistakes but also forces the company to depend heavily on a few experts who are deeply familiar with the technical structure of the products.

The situation is further complicated by the interaction between production and R&D. When new versions are introduced (for example, the BOD XL), the R&D department develops new structures, but the final documentation is not standardized immediately. This creates constant uncertainty in the definition of the BOM in the ERP system: sometimes this leads to real errors, other times to continuous revisions and unsynchronized updates.

The impact is also visible in the inventory management. It often happens that, once a printer has been built, the order is not properly closed in the ERP. As a result, the components still appear in stock, even though they have already been used. This makes the inventory unreliable and forces operators to manually verify the availability of parts, which is both time-consuming and inefficient.

In summary, the non-standardized use of Microsoft Dynamics Business Central generates a number of operational inefficiencies that translate into wasted time, errors in the management of BOMs, and low reliability of inventory data. To overcome these issues, the company should invest in widespread training for staff and in the standardization of technical documentation, so that the ERP system can become a truly effective tool rather than an obstacle in the production flow.

4.7 Material Flow Analysis – Spaghetti Diagram

To get a full picture of how production really works, looking only at the Value Stream Map is not enough. Lean literature reminds us that, beyond times and work sequences, it is also crucial to analyze the physical movements of materials. For this reason, I created a Spaghetti Diagram of the current layout, to visualize the actual paths followed by components and to identify where inefficiencies and complications arise (Figure 18).

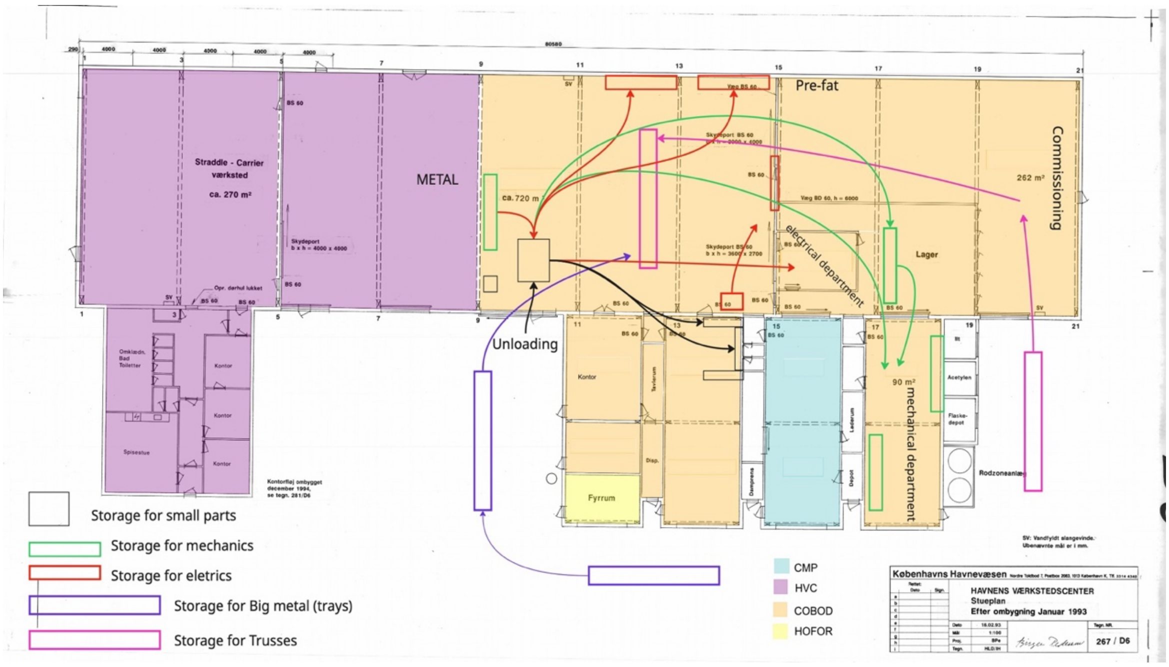


Figure 18:Spaghetti chart, material flow

Figure 18 shows the production layout with the main movement lines. The arrows represent the paths that materials take from truck unloading to the various storage areas and production departments.

In green, I traced the flow of mechanical parts. Here it is immediately clear that the dedicated racks are not all concentrated in the mechanical department but scattered across several areas, often far from where they are actually needed. This forces operators to move back and forth constantly, adding both time and effort.

In red, the path of electrical parts is shown. The situation is similar: racks are spread around wherever space was available, instead of being grouped in one area. As a result, operators face longer, crisscrossing routes, which reduces efficiency.

In purple, the storage points for large metal components are indicated. Since these parts cannot be kept inside the facility, they are left outside until needed. This, however, means they must be moved twice: once to bring them in for assembly or testing, and again to move them back out for shipping.

In pink, the paths of the trusses are highlighted. These are also stored outside, moved inside for commissioning and testing, and then transported back to the shipping gate.

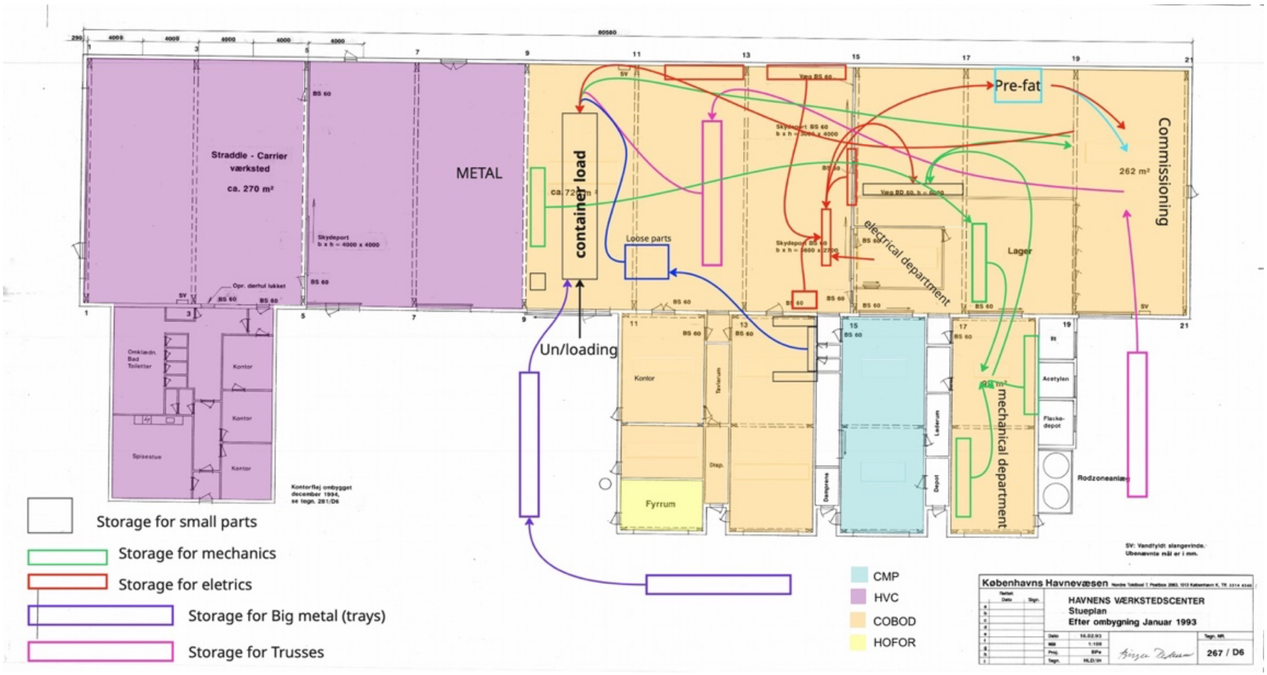
Finally, near the unloading gate, there are two specific areas (black boxes): one used for small deliveries and another for medium-sized pallets, which are then redistributed to either mechanical or electrical racks.

Overall, the picture that emerges is of a fragmented and non-linear flow. Materials travel back and forth multiple times, routes overlap, and operators often have to take long or repetitive paths. This results in extra time, uncomfortable operations, and a higher risk of errors or misplaced items.

There is also another aspect I was able to observe firsthand: the racks are not always used consistently. For convenience, especially smaller parts often end up in the wrong racks or in temporary locations, which creates confusion and uncertainty about where components are actually stored. This issue also has an impact at the information level: in the ERP, items are not always registered in the correct bin. As a result, the system data cannot always be trusted to locate materials. In practice, operators often have to rely on the storage managers directly, adding yet another step to the process.

4.8 Assembly Flow Analysis – Spaghetti Diagram

After looking at how incoming materials move through the facility, I created a second Spaghetti Diagram to show the flow during the actual assembly of a printer. Figure 19 helps to visualize how different departments hand work over to each other, from collecting parts all the way to final testing.



<u>Figure 19</u>:Spaghetti chart, assembly flow

The green path shows the mechanical flow. Once materials are unloaded and placed in storage, the mechanics gather all the components needed to build the carriages (Z-box, box, X-box, Y-box, and the printhead). These parts, coming from different storage areas, are brought into the mechanical department where assembly begins.

In parallel, the red path represents the electrical flow. The electricians start by collecting their parts and working on smaller components (such as offset sheets), while waiting for the carriages from the mechanics. Once these are ready, they are moved to the area in front of pre-fat, where the electricians take over and install the cabling, control boxes, and other electrical elements. At this stage, everything is transferred to the pre-fat area (shown in blue), which in the Value Stream Map corresponds to Quality Control. Here the connections are verified and the systems are checked against the software, essentially a preliminary test before the final trials. Next comes commissioning, this is where the trusses (pink path) are brought in, together with all the assembled mechanical and electrical parts. In this area, the printer is fully put together and switched on for testing.

Once the testing is complete, the printer is disassembled, and all the parts are moved to the container loading area for shipping. At the same time, the large metal components (purple path), which were not used during testing, are also taken to the shipping area. Finally, the loose parts (blue path), prepared on pallets by the packing lab, are added to the load before everything is packed into the containers.

Overall, this second spaghetti diagram reveals a fairly complex flow, with repeated steps and frequent back-and-forth between departments. While each step is necessary to assemble and test the printer correctly, the map also makes it clear that there are opportunities for improvement, especially in terms of logistics and coordination between departments.

4.9 Critical comparison of the two layouts

Looking at the two spaghetti diagrams side by side, one for the flow of incoming materials and the other for the assembly process, a clear picture emerges: the current layout is fragmented and far from efficient.

On the material side, storage is spread out across different areas of the facility. Mechanical and electrical parts are not grouped logically but placed wherever space was available. This results in long, crisscrossing routes, repeated handling, and an overall lack of flow. To make matters worse, small items are not always stored in their designated racks, which creates confusion and makes ERP data unreliable. In practice, operators often have to ask storage managers directly, adding further delays.

On the assembly side, the process is just as complicated. The constant back-and-forth between mechanics and electricians, the handovers in front of pre-fat, and the final move into commissioning mean that parts are moved several times before they ever reach the shipping area. Each step is necessary (assembly, quality checks, testing), but the way the layout is organized creates unnecessary loops and makes coordination harder.

In short, both diagrams reveal the same underlying problem: the layout does not support a smooth, linear flow. Instead, it forces operators and materials into detours, overlaps, and redundant steps. This not only increases time and effort but also raises the risk of errors, misplaced items, and communication gaps between departments. The numerous redundant routes clearly highlight a form of Muda, linked to unnecessary movements and transport.

Lean literature emphasises that layout design is crucial for reducing handling waste (Shingo, 1989).

All of this points to the same conclusion: reorganizing the layout by concentrating storage areas, aligning mechanical and electrical flows, and cutting out backtracking is a key step if the company wants to reduce lead times and improve efficiency across the board

CHAPTER 5: Proposal for Process and Layout Optimisation

5.1 Introduction to improvement

From the analysis in the previous chapter, several issues emerged that slow down production and affect its overall efficiency. The most obvious one is the high variability in lead times: sometimes a printer can be completed smoothly, while other times the process takes much longer. Part of this variability is unavoidable, since the production is highly customized and each machine is different. But by looking more closely at the individual tasks and the production layout, it’s clear that there are also internal factors that make this variability worse, and that some of it could actually be reduced.

To validate my findings, I had the chance to discuss them with key people in the company. In particular, with Edgar Skurvydas, who is in charge of the entire mechanical assembly line, and with Ole Ellinghausen, the Head of Production. Both confirmed that the results of my analysis such as the estimate of around 331 hours to build a BOD2 and the distribution of time across the different tasks are consistent with the reality of the production process. To get an even broader view, I also spoke with several operators on the shop floor, collecting their feedback about the challenges they face in their daily work (Appendix C).

Based on these insights, the next step is to identify possible solutions to reduce variability and make the production flow more stable, taking inspiration from the Lean principles of continuous improvement.

5.2 Introduction of extended SOPs and checklists

Checklists are not entirely new at COBOD: they are already used in certain steps of the process, for example during container loading, where they help verify that every component has actually been shipped. This simple tool has already proven useful in reducing common mistakes, such as forgetting accessories or smaller parts. At the same time, their use is currently limited to very specific situations and does not cover the entire production flow.

During my direct experience on the shop floor, I noticed that one of the biggest challenges is the training of new operators. Since there are no clear and documented operating instructions, onboarding becomes complicated and relies almost entirely on shadowing more experienced colleagues. For this reason, I believe that the systematic introduction of Standard Operating Procedures (SOPs), supported by operational checklists, could make a significant difference: they would provide clear guidance, reduce variability, and make daily work more repeatable and less dependent on individual experience.

There is also another important aspect: in a manual environment such as electrical and mechanical assembly, it is very difficult to measure productivity. There are no machines automatically recording times and outputs; everything depends on human work. This is why I believe that having, at the end of each day, a checklist showing the completed activities and the actual materials used would be very useful. With this information it would be possible to:

- estimate the average productivity of each operator,
- build a historical record to identify bottlenecks and balance workloads,
- collect real data to improve and stabilise Bills of Materials (BOMs).

BOMs, in fact, are currently one of the weak points: they often change, are not always updated properly in the ERP system, and sometimes the right version does not reach the production floor. In practice, operators do not always know which version they should follow. If every operator systematically recorded the materials used and the quantities assembled, this would provide real feedback to consolidate the BOMs and validate their accuracy.

From a methodological perspective, this proposal is closely aligned with Lean Manufacturing principles. Checklists are a practical application of Standard Work, as they define clear and repeatable procedures. They also act as Visual Management tools, making progress and controls immediately visible. They fit well with the 5S method, which encourages order and cleanliness, and reflect the spirit of Kaizen, continuous improvement driven by the contribution of the operators themselves.

Beyond the technical side, there are also important organizational and cultural benefits. Collecting data in a structured way reduces the dependency on a few highly experienced operators and helps distribute knowledge more evenly across the team. At the same time, using checklists fosters a more disciplined and transparent way of working, reinforcing a culture of responsibility and continuous learning.

Of course, this approach is not without its limitations. Operators may perceive the checklist as an additional layer of bureaucracy, and there is always the risk of superficial or incomplete compilation if the tool is not properly introduced. Moreover, some initial training and coaching would be required to ensure consistent adoption. These challenges are not unusual in change management processes, and they should be anticipated and addressed to secure long-term benefits.

It is important to emphasise that I do not see this tool as a rigid or permanent form of control. On the contrary, its role should be temporary, mainly to support the transition phase by providing the data needed to stabilise processes. Once BOMs have been consolidated and assembly procedures fully standardised, the checklist could be simplified and used primarily as a support for training and quality control.

Finally, looking ahead, this tool could naturally evolve into a digital version integrated within the company's ERP or MES systems. This would transform it from a paper-based support into a platform capable of recording real-time data, making it immediately available to all departments and further improving internal communication.

To illustrate this proposal in a concrete way, I developed a prototype of an operational checklist, which is presented in Figure 20.

DRAFT VERSION – PROPOSED IMPROVEMENT TOOL

COBOD

or date

APPENDIX A – EXAMPLE OF OPERATIONAL CHECKLIST

This appendix provides an example of a daily operational checklist designed for assembly activities in COBOD's production department. The purpose of this tool is to standardize processes, support training, and collect real data for BOM (Bill of Materials) validation and productivity analysis.

OPERATIONAL CHECKLIST – BOD2 ASSEMBLY

DOCUMENT CODE:	SOP-ASM-EL-001
DATE:	___ / ___ / 2025
OPERATOR:	____________________
DEPARTMENT:	☐ Electrical ☐ Mechanical ☐ Other _______
WORKDAY:	___ / ___ / 2025
SUPERVISOR SIGNATURE:	____________________

SECTION A – ACTIVITIES PERFORMED

No.	Activity/Component	Planned Qty (BOM)	Actual Qty Assembled	Materials Used (Code/Description)	Notes / Issues
1					
2					
3					

SECTION B – QUALITY AND SAFETY CHECKS

☐ All components comply with technical drawings

☐ No missing or unauthorized substitutions of materials

☐ Workstation left tidy and in 5S condition

☐ Non-conformities reported to supervisor

SECTION C – DAILY OPERATOR OUTPUT

Total number of assemblies completed: _______

Estimated time for each activity: _______ h

Main issues encountered: ________________________________

Improvement suggestions: ________________________________

COBOD International A/S
Skudehavnsvej 17A
2150 Nordhavn, Denmark
CVR-NR: 38151886

cobod.com/contact
+45 9290 9066
info@cobod.com

Figure 20: Prototype of operational checklist for assembly activities

5.3 ERP & BOM standardisation

One of the main issues that emerged in Chapter 4 is the lack of a stable and reliable Bill of Materials (BOM). Because design changes are frequent and communication between departments is not always smooth, the BOMs that reach the office are often incomplete or outdated. On the shop floor, operators usually know thanks to their experience how to put the product together. The real struggle happens in the office: people who have to build or update the BOMs in the ERP system do not have the same direct visibility, and since documentation is fragmented and scattered, they often work without a clear and accurate reference.

This is not just my impression. As the Head of Production explained, "the creation, handover and revision of BOMs must be improved, as well as the overall understanding of our business processes and ERP across the organization" (Ole). His words highlight a bigger cultural issue: many people in the company are not comfortable with the ERP system. Often they avoid using it simply because they never received proper training. As a result, key knowledge ends up concentrated in just a few individuals, while others rely on manual workarounds outside the system, slowing things down and creating unnecessary risks of error.

Another problem arises when small sub-assemblies are created directly in the ERP and added to the printer BOM without being properly validated. In reality, these assemblies often do not reflect what is actually built in production. For operators this is rarely an obstacle, because they know how to handle the assembly anyway. But for the ERP it creates major inconsistencies: wrong materials are recorded as consumed, stock data becomes unreliable, and, even worse, the financial side is distorted. If the ERP tracks the consumption of incorrect parts, the final cost of the product no longer matches the real cost, creating a gap between what accounting reports and what actually happens in production. Edgar also pointed out that poor stock handling and lack of documentation on incoming parts make this situation even worse, leading to extra delays and rework.

The same inefficiency can be seen in the shipping process. Every time a shipment has to be prepared whether it is a complete printer, spare parts, or just a small order, the packing list and shipping invoice are often created manually in Excel. This takes up a huge amount of time and increases the chance of mistakes. The frustrating part is that Business Central already has the functionality to generate these documents automatically; it simply needs to be properly configured. Setting this up once would save hours of manual work for every shipment and ensure consistency across all orders.

To fix these issues, the company needs a more structured way of managing BOMs. A modular structure would help separate the components that are always the same (like structural parts or standard cabling) from those that change based on customer specifications. This would make updates easier to handle and reduce the number of revisions. At the same time, integrating ERP more closely into day-to-day operations would ensure that the latest and most accurate BOM is always accessible. The temporary use of checklists, as described earlier, could feed back real shop floor data to the office, helping validate BOMs and align the "as designed" with the "as built". Over time, this would not only stabilise BOMs but also make the ERP database much more reliable.

In the long run, the ERP should become the single source of truth for everyone: design, procurement, finance, and production. For this to happen, clear responsibility for updates must be established, and just as importantly employees across departments need training so that more people feel confident using the system. This would reduce the dependence on a few individuals, improve collaboration, and make sure that both operational and financial data truly reflect reality.

Application to Business Central.

Business Central already has many of the tools needed to move in this direction. Production BOMs and Routings can be structured in a modular way, making it easier to manage both standard and customised printer configurations. The system also supports version control, so that updates can be documented and linked directly to production orders. In addition, with MES extensions, operators could record material consumption and working times directly at their workstation, automatically feeding this data back into the ERP. This would make financial calculations such as comparing standard with actual costs much more accurate, because they would be based on real production data.

Looking further ahead, integrating Business Central with a MES system would make it possible to track production in real time, transforming the BOM from a static document into a dynamic reference that reflects both technical and financial reality.

Based on my time working closely with the company, I am convinced that these proposals are not just about "tidying up processes." They would have a real and visible impact on quality and efficiency, while cutting down bureaucratic variability by as much as 50%. In other words, they would help make production more stable, more transparent, and much closer to the actual performance of the shop floor.

5.4 Cross-training and resource balancing

One of the clearest issues that came out of the analysis is how much the company relies on just a few highly skilled people for the most critical phases of production especially in electrical assembly, FAT (Factory Acceptance Test), and commissioning. These colleagues are incredibly capable, but the problem is that whenever they are unavailable, or when too many urgent tasks overlap, the whole process slows down.

For new employees, the challenge is just as big. The learning curve is long, because onboarding still depends almost entirely on shadowing experienced colleagues, with no structured documentation or clear training path. I noticed this myself during my internship: I was assigned to work with the Head of Production, but since he was often tied up with other priorities, it wasn't always obvious where to begin or how to learn in a systematic way. That experience showed me just how fragile onboarding can be when it depends only on the availability of a few people, instead of on shared systems and tools.

A practical way forward is to introduce cross-training supported by a skill matrix. This idea is not new it has been widely applied in Lean organizations for decades. At Toyota, for instance, skill matrices are used to make workforce capabilities visible and to guarantee flexibility across assembly lines (Liker, 2004). The concept is simple: the matrix lists operators against key production tasks and shows their competence level (basic knowledge, independent, or expert). What looks like a simple grid quickly becomes a powerful management tool, because it makes clear where the team is strong and where it relies too heavily on just one or two people.

Once this overview is in place, the matrix can guide a structured cross-training plan. If, for example, only one or two operators are able to handle commissioning, others can be progressively trained until at least three people reach an independent level. This is very much in line with what Womack and Jones (1996) describe in Lean Thinking as the value of "multi-skilled workers": people who can flexibly move across tasks, giving the whole system more stability. Over time, the matrix also becomes a living document updated after each training session, it turns competence development into something visible and measurable.

The matrix also helps with balancing resources. Instead of always pulling the same experts into FAT, tasks can be distributed more evenly across the team. This doesn't just reduce pressure on individuals, but also frees up senior staff to dedicate more time to quality control or to supporting R&D in testing and validation, exactly the kind of needs that Ole and Edgar highlighted in the interviews. From a Lean perspective, this also means reducing muri (overburden), which Ohno (1988) identified as one of the three major forms of waste.

Sharing skills more widely makes the company less vulnerable to absences or sudden changes, while employees themselves gain confidence as they expand their abilities. Onboarding becomes faster, variability in critical phases is reduced, and production flows more smoothly. Most importantly, cross-training embodies the Lean principle of "respect for people": it is not just about covering operational gaps, but about giving people opportunities to learn and grow, and about building a motivated, versatile, and resilient team.

5.5 Production layout and internal logistics: challenges and opportunities

The analysis carried out with the Value Stream Map and the spaghetti charts highlighted several inefficiencies in the current organisation of space and material flows. These tools were extremely useful for understanding where waste, delays, and unnecessary movements occur, in other words, why the production process often feels less smooth than it could be. At the same time, it is important to note that the situation observed describes a reality that will soon change significantly. In December, COBOD will relocate to its new facility in Taastrup, marking the beginning of a completely new phase for the company.

At present, COBOD operates in a free-zone in the Copenhagen harbour area, but the city has started work on expanding the metro line, which will run directly above the company's current buildings. For this reason, COBOD was required to vacate the site and find a new location. What initially appeared to be a constraint quickly turned into an opportunity to fundamentally rethink the way the company is organised.

One of the main objectives in selecting the new site was to bring all departments under one roof. Until now, R&D, Sales, and Production have been spread across three separate buildings, even if they were located close to one another. This fragmentation has often complicated communication and day-to-day collaboration. With the move to Taastrup, COBOD will finally be able to integrate all functions within a single space. This change is more than just a logistical improvement: it is an opportunity to create a more cohesive, efficient, and connected working environment.

From a production perspective, the new facility also represents the perfect chance to address many of the issues revealed by the studies of the current layout. Today, operators often need to cover long distances or move between different areas just to retrieve components or materials. With a more carefully designed layout, these inefficiencies can be eliminated at the root, allowing material flows to become much more linear and stable.

The following sections will therefore outline the main issues with the current layout, explore potential Lean-based solutions to optimise internal logistics, present guidelines for the design of the new facility, and finally, describe the expected benefits in terms of efficiency, quality, and reduced variability.

5.5.1 Organising Stock for Stability and Flow

One of the most frustrating issues I noticed in production is the lack of reliability in warehouse management. It often happens that an operator suddenly discovers a component is missing not because it was never ordered, but simply because someone took it off the shelf without recording it in the system. In those cases, the ERP still shows the item as available, but in reality, it's gone. The result is that assembly stops, time is wasted looking for alternatives, and the entire flow slows down. This is not just a technical problem: it reflects a deeper cultural issue, with little standardisation and even less discipline in how materials are handled.

The same applies to BIN codes. In theory, every part should have a fixed location, both physically in the warehouse and digitally in the ERP. In practice, though, this rule is often ignored: items end up wherever there is space, or they are moved without updating the system. This creates a chain reaction: experienced staff eventually figure things out, but newcomers, and there are many, especially student assistants struggle to navigate such a confusing setup.

The first step forward would be a complete reorganisation of BIN codes: each component should have a logical, permanent location, updated in the ERP. On top of this, it would be extremely useful to create technical sheets for each sub-assembly, listing not only the components and their quantities but also the BIN location of each item. This way, even a new operator could quickly become autonomous without constantly asking for help. The best part is that these sheets wouldn't even require extra manual work: if order and standardisation were properly followed, they could be generated automatically by the ERP, turning them into a practical and reliable tool for both daily operations and training.

Another important step would be to rethink the logic of shelf organisation. At present, storage is far too scattered: parts used in the same sub-assembly or production step are often placed far apart, forcing operators into constant back-and-forth movements. A much better solution would be to organise storage around the assembly line itself, grouping together materials that are used in the same order or stage. This would cut down on wasted movements, make picking more intuitive, and create a smoother flow across the shop floor. Practically, this reorganisation should be guided by the 5S method: remove unnecessary items, assign each part a clear and visible location, keep the area tidy, establish shared rules, and most importantly develop the discipline to sustain them over time. This means clearly labelled shelves, frequently used materials placed in easy-to-reach spots, and visual signals to show at a glance what is available and what is missing.

With this approach, the warehouse would stop being a bottleneck and instead become a true ally of production: orderly, intuitive, and accessible to everyone. Operators would spend less time searching for parts, new employees could get up to speed much faster, and most importantly stock levels would finally become reliable. In other words, what is now a weak point could become one of the strongest foundations for production stability.

5.5.2 From Bottleneck to Standardisation: Electrical and Mechanical Perspectives

When it comes to storage, the electrical department is actually one of the most organised parts of production. The team takes care of its own stock, keeps everything in order, and generally knows exactly where things are. Walking through their shelves, you immediately get the impression of tidiness and control. But the real issue isn't about where the parts are stored, it's about what isn't written down. For anyone outside the department, it's almost impossible to understand how things work. Processes aren't documented, the components aren't clearly described, and most of the know-how exists only in the heads of the people who have been doing the job for years. This makes the department effective for those inside it, but closed off for everyone else. In a small company like COBOD, where teamwork and flexibility are essential, that's a real risk.

From a process perspective, electrical assembly is also one of the longest and most demanding stages of the printer build. Wiring, assembling control panels, and integrating systems require both skill and patience, and they inevitably slow the flow down. The bottleneck is clear. Yet it's also something that could be solved quite directly: with just one more person. In the past, when the electrical team had up to four members, the difference was obvious, the workload was lighter, production moved faster, and delays were less

common. Today, with a BOD2 taking about 300 hours to build in total, and around one-third of that time tied up in electrical tasks, adding one more person could realistically save 50 to 70 hours per printer. That's a significant improvement in both lead time and variability.
The picture is different in mechanics. Here the team usually counts between two and five people: one or two focus on the assemblies, while the others move to commissioning and testing. The procedures are more standardised, the documentation is clearer, and the overall variability is much lower than in the electrical team. In fact, mechanics often help stabilise the whole production flow, showing how much of a difference good standardisation makes.
For the electrical department, the next step has to be more than just adding people, it has to be about creating structure. A useful way to think about this is through the PDCA cycle (Plan–Do–Check–Act):

- Plan: set specific goals, like cutting electrical assembly time by 20% and making processes clearer for colleagues outside the department.
- Do: bring in one more operator and start developing technical sheets and standard procedures.
- Check: measure the impact, both on the total hours needed and on how quickly new or external staff can work independently.
- Act: take what works, make it permanent, and keep adjusting when new problems show up.

As Lean literature points out (Deming, 1986; Rother & Shook, 1999), the strength of PDCA is that it's simple, flexible, and repeatable. In an environment like COBOD's, where every printer is highly customised, this approach offers a structured way to test improvements, see what works, and slowly bring stability to processes that today feel fragile. And while here the focus is on electrical assembly, the same mindset could be applied across the company in logistics, procurement, documentation, even quality control. PDCA isn't just a tool to fix one bottleneck: it's a way of working that can make the whole organisation stronger over time.

5.5.8 Quality control and commissioning

One of the most delicate moments in the production process is what happens before the FAT (quality control). In theory, this stage should only serve as the final confirmation that the printer works properly before commissioning and shipment. In practice, however, this is where most problems emerge: defects in structural components (such as carriages or trusses), misalignments, or even missing parts. As Ole pointed out during the interviews, "quality issues of incoming parts, especially sheet metal elements like carriages and trusses, are first caught at the FAT stage, when often there is no longer time to fix them before shipping."

The commissioning phase further amplifies this variability. Today, setting up and dismantling a whole printer just to test a few mechatronic modules or software functions can take up to three to five days. This is a huge investment of time and resources for activities that add no real value to the product, while at the same time slowing down the flow and creating frustration for operators. As Ole emphasised, "setup and take down of printers in commissioning are extremely time-consuming," and a practical solution would be the use of dedicated test benches.

From a Lean perspective, this situation highlights the absence of the jidoka principle, or "quality at the source." If defects are only discovered at FAT, the process is reactive rather than preventive. To change this, COBOD could introduce a series of concrete measures:

- Quality control on internal orders: as already discussed in the sections on warehousing and procurement, many issues do not stem from suppliers but from the way orders are managed internally. There is often no clear and updated vision of what is actually happening in production, which leads to ordering the wrong quantities or even the wrong versions of components. The result is twofold: on the one hand, missing critical parts when they are needed; on the other, excess materials that take up valuable space. Introducing a systematic review of orders, checking that quantities, versions, and priorities match the real needs of production would reduce errors upstream and prevent issues from only becoming visible at FAT.
- Modular testing with dedicated benches: instead of assembling a full printer every time, mechatronic subsystems and control panels could be validated separately on test benches. This would drastically reduce FAT times and make commissioning more stable and predictable.
- Standardised commissioning checklists: as discussed in earlier sections of this thesis, introducing operational checklists would make the process less dependent on individual expertise, ensure consistency, and lower the risk of errors.
- Stronger integration with R&D: many of the difficulties in pre-FAT stem from fragmented or outdated documentation. Edgar highlighted that "mechanical assembly is often where we discover that parts don't fit or have been produced incorrectly." Establishing a more structured communication flow between

production and R&D would allow faster updates to documentation and fewer recurring mistakes.

Applying the PDCA cycle (Plan–Do–Check–Act) here means turning improvement into a continuous process:

- Plan: set clear objectives, such as reducing FAT rework cases by 50%.
- Do: implement order verification, test benches, and commissioning checklists.
- Check: track defect rates, average FAT times, and the number of rework cases.
- Act: consolidate the improvements and extend good practices to other departments.

Finally, another practical step would be to introduce a kanban system for components and sub-assemblies during pre-FAT. Today, operators often discover too late whether a part has already been tested, is ready for use, or still needs checking. Simple visual signals such as colour-coded tags (green = tested, yellow = pending, red = needs rework) would immediately show the status of each item without relying on memory or verbal updates. Beyond reducing mistakes, this would support smoother handovers between departments and make the process more transparent. In Lean terms, kanban would help eliminate the wastes of waiting and searching, complementing the other measures and turning pre-FAT from a source of variability into a predictable, well-structured stage of production.

The benefit would go beyond efficiency alone. Strengthening the pre-FAT stage would mean delivering more reliable printers, reducing issues during installation, and building stronger trust with customers. In other words, quality would no longer be something checked only at the very end, but a principle embedded in every step of the production process.

5.6 Future State Value Stream Map

When analysing production through a Lean perspective, it is important to clarify that both the current state and the future state Value Stream Maps represent idealised scenarios. They assume that materials arrive on time, no rework is required, and every process flows without unexpected interruptions. In reality, variability will always exist, but by visualising a “clean” scenario, it becomes possible to identify the true potential of the process and the impact of introducing new practices.

Previous studies (Reka, 2022) have shown what can be achieved under best-case conditions. For example, the mechanical assembly of one carriage can be completed in about one hour, meaning that one person could theoretically finish all carriages in roughly 15 hours. With two workers, this time drops to about one day. Similarly, in electrical assembly, two workers can complete the Z and Y carriages in about two days, while the E-box and printhead each require one additional day. If three to four electrical operators work in parallel, the entire phase can be finished in two days. These benchmarks provide useful reference points for assessing what is realistic in COBOD's context.

5.6.1 Current state vs. future state comparison

Procurement & Warehousing

- Current: incoherent orders, frequent stock-outs, bin codes often ignored, variable lead time (3–5 days).
- Future: verified and standardised orders, updated and respected bin codes, 5S in the warehouse, kanban for critical items, ERP-generated assembly sheets.
- Target: materials prepared in 1/2 day.

Mechanical Assembly

- Current state:1 operator, 15 hours (~2 days)
  2 operators, 7-8 hours (~1 day).
- Problems: workflow depends heavily on how many people are available; materials are not always pre-kitted, creating delays.
- Future state (implementation): apply kitting of all materials before assembly, Reorganise BIN codes and apply 5S to reduce wasted time, maintain standard of 1 carriage per hour per person.
- Target: 1-2 days, depending on number of operators.

Electrical Assembly

- Current state: with 2 workers Z & Y carriages (2 days); E-box + printhead sequential (+2 days).
- Total = ~4 days.
- Problems: bottleneck due to limited staff, lack of documentation, no parallelisation possible.
- Future state (implementation): add a third operator.

Distribute tasks:

- 2 workers on Z & Y carriages (2 days).
- 1 worker on E-box + printhead in parallel (1 day each).
- Introduce SOPs and technical sheets to reduce variability.
- Target: reduced from 4 days to 2/3 days.

Commissioning & Quality Control

- Current state: 5-6 days, often with full printer setups and dismantling, many defects only discovered at this stage.
- Problems: highly variable process, strong dependency on senior staff.
- Future state (implementation):introduce dedicated test benches for subsystem validation, apply commissioning checklists to ensure consistency, use kanban signals (green/yellow/red) to track subsystem status.
- Target: reduced from 5-6 days,to 3 days.

Shipping

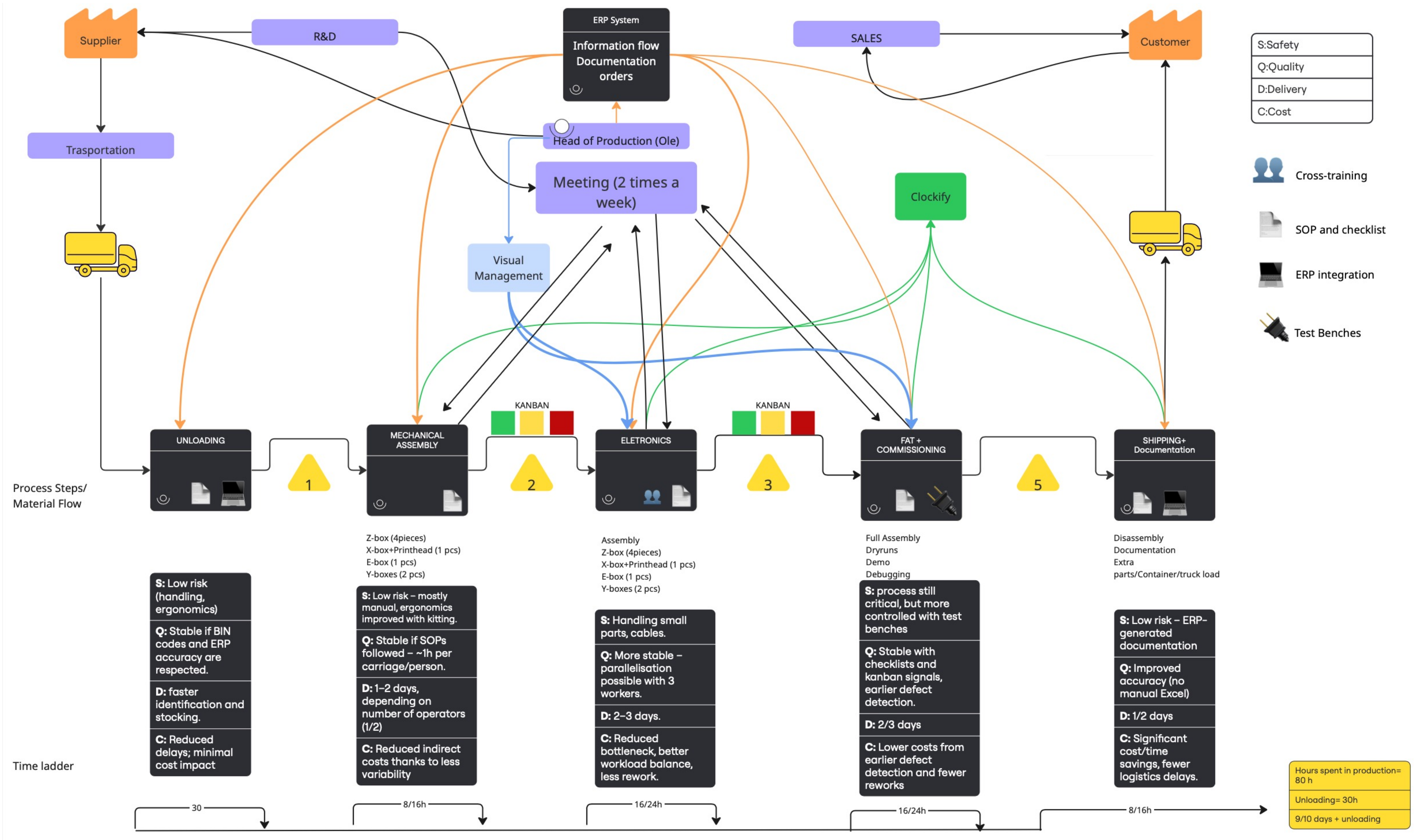
- Current: 4–5 days, high variability, shipping documentation prepared manually, frequent errors.
- Future: automatic generation of packing lists and shipping invoices from ERP, smoother integration between departments.
- Target: completed in 2 days

Table 5:Current state vs Future

STATE	TOTAL TIME (DAYS)
Current	25-28
Future	9-10

In summary, the proposed improvements would have a substantial impact on production efficiency. The overall lead time could be reduced by nearly 70%, provided that the processes are standardised, cross-training is implemented to reduce dependency on a few experts, and visual management tools such as kanban are adopted. At the same time, ERP data and stock levels would become more reliable, while the entire production flow would gain in stability and predictability. This is particularly important in view of the relocation to the new Taastrup facility, where a smoother and more coordinated workflow will be essential.

It should be emphasised, however, that the estimated 9–10 days represents an idealised future state, assuming no delays, no rework, and a perfectly smooth process. In practice, some level of variability will always remain. Nevertheless, this scenario highlights the potential gains achievable through targeted actions (Figure 21).



<u>Figure 21</u>:Future Stream map, ideal scenario

5.7 Critical Overview of the Current Layout

Before addressing the proposal for the new production site, it is essential to briefly reflect on the weaknesses of the current configuration. The analyses conducted through Value Stream Mapping and spaghetti diagrams have highlighted several structural inefficiencies that, although tolerable in a pioneering phase, represent significant obstacles to scalability and standardisation. These findings serve as a useful benchmark: rather than optimising the existing site, they provide valuable lessons for designing the new facility more effectively.

To summarise the main limitations of the current layout, Table 6 presents the most critical issues identified, together with their operational impact. This overview allows for a clear understanding of which aspects must be addressed and avoided in the design of the new production flow.

Table 6:Issues identified

IDENTIFIED ISSUE	VSM / SPAGHETTI DIAGRAM	IMPACT ON EFFICIENCY
Excessive operator movements	Spaghetti diagram shows long, overlapping, and crossing paths	Increased transportation time, higher operator fatigue
Lack of linear process flow	VSM highlights back-and-forth steps between work areas	Waste of motion and handling, delays in operations
Non-standardised workstations	Direct observation shows ad-hoc arrangement of tools and stations	Difficult to standardise, high variability, reliance on individual skills
Overlap between materials and operators	Material storage areas interfere with assembly zones	Congestion, safety risks, and higher probability of errors
Absence of visual management	No clear signs or visual distinction of areas	Lack of transparency, longer training times, reduced process control

5.8 Design Principles and Structure of the New Site

The design of the new production layout has been guided by the limitations identified in the analysis of the current configuration. Rather than attempting to optimise a setup that was developed in a “pioneering” phase, the relocation to the Taastrup facility represents an opportunity to establish from the outset a rational, scalable organisation aligned with lean manufacturing principles.

The new site consists of a large area dedicated to storage and production, as well as an adjacent office zone with reception and administrative spaces. The general floor plan (Figure 22) highlights the subdivision into two main halls: the first hall, located near the offices, which is more suitable for storage activities and assembly operations, and the second hall, more isolated, designated for the final phases of commissioning, testing, and shipping. This spatial organisation naturally separates the upstream and downstream activities of the production process, thereby reducing interferences and ensuring clearer management of flows.

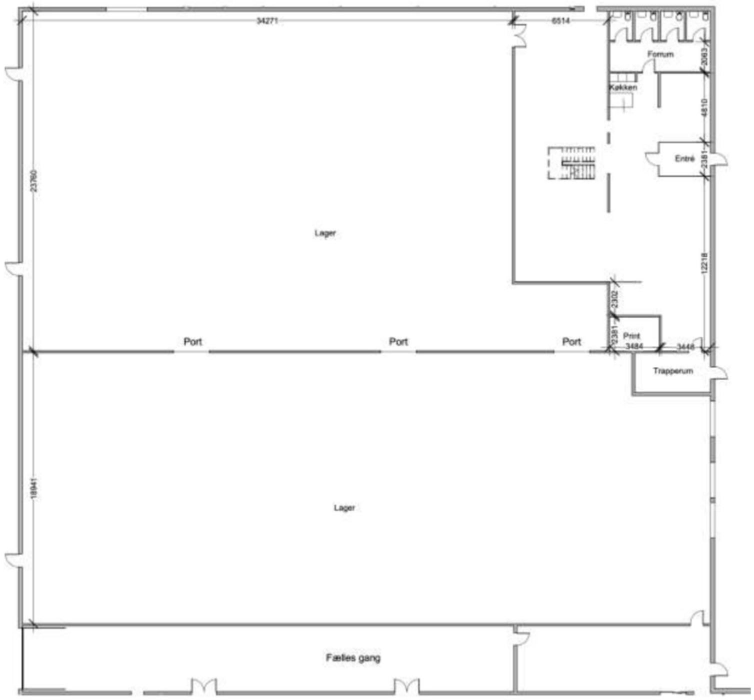


Figure 22:Floor plan of the new facility in Taastrup (Source:Company photo archive, internal data)

The main criteria that have guided the layout design can be summarised as follows:

- Linearity of flow: ensuring a clear path for materials, from raw material reception to shipping, without unnecessary backtracking or intersections.
- Functional separation of areas: clear distinction between storage, assembly, quality control, and testing zones.
- Integration of kitting: preparing material kits before assembly to reduce operator movements and handling time.

- Intermediate quality control: introducing a checkpoint between mechanical and electrical assembly to detect defects early.
- Customer visibility: including a dedicated showroom with a COBOD printer to strengthen the company's image.
- Optimised logistics: placing receiving and shipping areas close to loading docks to minimise internal transport.
- Scalability and flexibility: adopting a modular configuration adaptable to new product lines or increased volumes.

Based on these principles, two alternative layout configurations have been developed. Both are consistent with the criteria described above, but differ in terms of spatial organisation and the degree of compactness of the production flow. The two alternatives will be presented and analysed in the following sections, with a direct comparison of their respective strengths and weaknesses.

5.8.1 Proposed Layout Version A: Linear Flow

The first configuration is designed around a linear flow, meaning that materials and products move step by step from the receiving area to the shipping zone without unnecessary backtracking. The goal is to create a process that is as clear, organised and efficient as possible, while keeping internal movements to a minimum. The overall arrangement can be seen in Figure 23, which shows how the different areas are positioned inside the Taastrup facility.

The flow starts in the receiving and raw material storage area, placed near the upper loading docks to simplify deliveries. All incoming materials are handled here, except for the trusses: because of their size and weight, they are not moved during the early stages of production but only when the unit reaches commissioning. For this reason, it is more practical to unload and store them directly in the second hall, next to the commissioning and testing areas, so they do not need to be shifted multiple times.

The main storage is organised into separate sections (for mechanical components, electrical parts, small items, and bulky materials), but all kept within the same zone to make picking faster and kitting more straightforward. Next to it is the kitting area, where materials are grouped into kits before being delivered to the assembly stations. From there, the process continues with mechanical assembly, carried out in a large open space for building the main structures of the printers. After this step, an intermediate quality control station checks the mechanical assemblies to make sure any issues are caught early, before moving on to the electrical phase.

The next step is electrical assembly, with standardised workstations for wiring and component integration. As already highlighted in the future stream map study, having the mechanical and electrical areas side by side is a real advantage: if at least three operators are working in the electrical section, they can immediately start on a unit as soon as it leaves mechanical assembly. This allows several electrical stations to work in parallel, reducing lead times and increasing overall productivity.

Finally, the flow moves into the second hall, where commissioning and final testing take place in an isolated space. This ensures safety, accuracy, and minimal interference with ongoing production. The finished units are then moved to the shipping area, positioned close to the exit doors to simplify loading and outbound logistics.

In addition to the production flow, the layout also includes a dedicated showroom space inside the first hall, where a COBOD printer can be displayed to customers visiting the facility. Visitors would enter through the offices and then access the showroom directly, without interfering with production activities. This solution not only improves the company's professional image, but also offers an opportunity to showcase COBOD's technology in a real production environment.

Figure 23:Proposed Layout Version A (Linear Flow)

Overall, this layout is strong because of its clarity and orderliness: the flow is easy to follow, movements are reduced, and the warehouse organisation supports efficient preparation of kits. Its main limitation, however, is that it can be less flexible: a very linear setup leaves less room for adjustments if product requirements change or if production volumes vary significantly.

5.8.2 Proposed Layout Version B: Alternative Configuration

The second proposed configuration introduces some additional elements compared to the linear layout, with the aim of improving communication and supporting future development activities. The layout is shown in Figure 24, where the arrangement of the main areas is complemented by dedicated spaces for R&D and material testing.

In this version, a small R&D laboratory is included near the assembly areas. The purpose of this space is twofold: on the one hand, it facilitates direct communication with both the mechanical and electrical assembly teams in case of issues related to prototypes, drawings, or design modifications; on the other hand, it provides a flexible environment for experimentation and the development of new solutions. By placing R&D closer to production, feedback cycles can be shortened and collaboration between engineering and manufacturing teams can be enhanced.

Another important feature of this layout is the integration of a material laboratory and a dedicated storage area for chemical materials used in 3D printing. At present, COBOD's printer and material experts are located in TF, a separate site from the main production facility. This physical distance makes coordination more difficult and slows down experimentation. In the new facility, however, bringing these activities under the same roof would make it possible to centralise both material storage and testing capabilities. This would improve efficiency, simplify logistics, and strengthen the link between material development and product assembly.

As in the linear configuration, the overall production flow remains coherent: raw materials enter through the receiving area and pass through kitting, mechanical assembly, intermediate quality control, and electrical assembly before reaching commissioning, testing, and finally shipping. At the same time, this version provides additional flexibility and value by incorporating spaces that directly support innovation and knowledge exchange.

The main advantage of this configuration lies in its ability to combine production with R&D and material development, fostering faster problem-solving and supporting long-term technological growth. A potential limitation, however, is that the inclusion of additional areas reduces the amount of free space available for core production, which may create constraints if production volumes increase significantly.

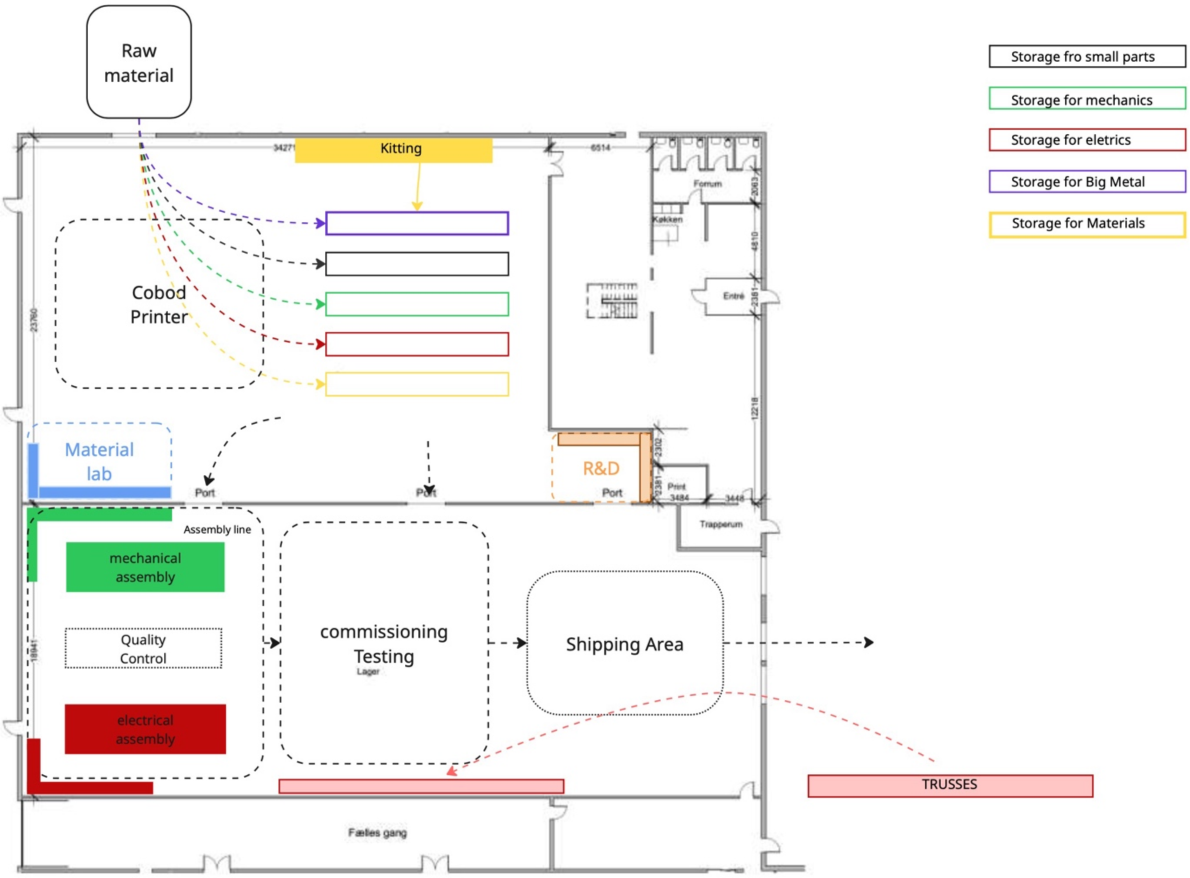


Figure 24:Proposed Layout Version B

5.8.3 Comparative Analysis

To evaluate the two proposed configurations, a comparative analysis was conducted based on the key design principles outlined earlier (Table 7). The aim is to highlight the main strengths and weaknesses of each layout and to understand which solution provides the best fit for the company's future needs.

The comparison shows that Version A stands out for its linearity and simplicity: the flow is straightforward, transparent, and well suited to large-scale production, with minimal risk of overlaps or congestion. Version B, on the other hand, offers a more integrated approach by including an R&D laboratory and a material testing area within the production site. This setup allows the full production cycle of a printer to take place within one hall, improving collaboration between departments and making it easier to adapt to new requirements.

Table 7: Comparative analysis

ASPECT	VERSION A	VERSION B
Material flow clarity	Very clear, fully linear, easy to follow	Clear, though with additional functional areas integrated
Space usage	Requires more space across the facility	More compact and efficient use of one hall
Flexibility	Limited, strongly sequential and less adaptable	High, integrates R&D and materials, enabling quick adjustments
Support for R&D	None	Dedicated R&D lab and material testing area
Customer visibility	Showroom space for COBOD printer included	Showroom plus integration of material expertise on site
Scalability	High, linear design supports higher volumes	High, consolidating the entire printer cycle in one hall improves communication and supports future growth

In summary, Version A prioritises clarity and streamlined scalability, while Version B combines production, innovation, and flexibility in a single integrated environment, which may better support continuous improvement and cross-functional communication.

5.8.4 Final Recommendation and Expected Benefits

Both proposed layouts would represent a significant improvement over the current configuration. After evaluating their respective strengths, the recommended solution is Version B, as it not only integrates production and R&D activities within the same facility, but also incorporates material expertise and storage directly into the production site. This represents a major step forward compared to the current situation, where COBOD's material specialists and equipment are located in a separate facility (TF), limiting collaboration and slowing down experimentation.

The implementation of the new layout is expected to generate several tangible benefits for COBOD:

- Operational efficiency: shorter transport routes and reduced handling waste.
- Process reliability: clearer separation between mechanical assembly, electrical assembly, and testing.

- Flexibility: ability to adapt to new product requirements, supported by the proximity of R&D and production.
- Innovation capacity: dedicated spaces for prototyping and experimentation, plus a material laboratory on site.
- Customer experience: a showroom area that strengthens COBOD's professional image during client visits.
- Material development: integration of chemical material storage and testing directly in the production cycle, improving coordination and reducing delays.
- Future growth: a facility optimised not only for today's processes but also scalable to support COBOD's ambitions.

In conclusion, adopting the alternative configuration will not only resolve the inefficiencies of the current site but also enable a more integrated approach to production, materials, and innovation, providing COBOD with a solid and flexible foundation for future development.

Conclusions

This thesis aimed to support COBOD during its growth by analysing the current production system and designing a new layout for the facility in Taastrup. The work was not only about fixing small inefficiencies, but about creating a clear vision of how production can become more efficient, flexible, and connected to innovation.

The study showed that the existing organisation, while suitable in the early pioneering phase, has limits: material flows are complicated, processes are not always standardised, and functions are not fully integrated. By mapping the processes and identifying problems, it became clear how these issues reduce efficiency and make scaling more difficult.

To address this, two new layouts were proposed for the Taastrup site. Both follow lean principles, aiming to reduce waste, improve flows, and make production more transparent. The comparison highlighted that the linear version is very clear and easy to manage, but the second version, which also includes R&D and material expertise inside the facility, offers greater long-term benefits.

The main results of this thesis can be summarised as follows:

- COBOD's production can be reorganised into a clearer and more efficient structure.
- The move to Taastrup is an opportunity for optimisation, but also for organisational development.
- A layout that connects production, materials, and R&D provides the strongest basis for future growth.

Future Perspectives

Looking forward, some next steps are important. These include monitoring key performance indicators (KPIs) to measure the real impact of the new organisation, improving digital integration with the ERP system, and possibly introducing automation in material handling. As production volumes grow, the layout may need further changes to keep it flexible and scalable.

In conclusion, this thesis shows how a structured and lean approach can transform a complex production environment into a clear and future-oriented system. The proposed layout is not only a solution to current problems, but also a strategic tool for COBOD's growth and innovation in the years ahead.

Bibliography

- Imai, M. (1986). Kaizen: The key to Japan's competitive success. McGraw-Hill.
- Imai, M. (1997). Gemba Kaizen: A commonsense approach to a continuous improvement strategy. McGraw-Hill.
- Liker, J. K. (2004). The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer. McGraw-Hill.
- Shingo, S. (1989). A study of the Toyota production system: From an industrial engineering viewpoint. Productivity Press.
- Ohno, T. (1988). Toyota Production System: Beyond Large-Scale Production. Productivity Press
- Ford, H. (1926). Today and Tomorrow. Garden City Publishing. (Original work published 1926; often cited for the 1913 moving assembly line).
- Gilbreth, F. B., & Gilbreth, L. M. (1917). Applied Motion Study: A Collection of Papers on the Efficient Method to Industrial Preparedness. Sturgis & Walton Company.
- Iuga, M. V., & Kifor, C. V. (n.d.). Lean manufacturing: The when, the where, the who. "Lucian Blaga" University of Engineering, Sibiu (Romania).
- Olutade, O. (2021). The impact of Kaizen practices on organisational performance. Journal of Business and Management
- Buer, S. V., Strandhagen, J. O., & Chan, F. T. S. (2018). The link between Industry 4.0 and lean manufacturing: Mapping current research and future directions. International Journal of Production
- Tommelein, I. D. (2008). Poka-yoke and construction: Error proofing in dynamic environments. Journal of Construction Engineering and Management,
- Sanders, A., Elangeswaran, C., & Wulfsberg, J. (2016). Industry 4.0 implies lean manufacturing: Research activities in Industry 4.0 function as enablers for lean manufacturing. Journal of Industrial Engineering and Management.
- Sundar, R., Balaji, A. N., & Satheesh Kumar, R. M. (2014). A review on lean manufacturing implementation techniques. Procedia Engineering, 97, 1875–1885.
- Moen, R. (2010). Foundation and history of the PDSA Cycle. Paper presented at the 16th Annual International Deming Research Seminar, February 2010. Associates in Process Improvement, Detroit, USA.

- Zhang, A. (2014). Quality improvement through Poka-Yoke: From engineering design to information system design. International Journal of Six Sigma and Competitive Advantage
- Reka, N. (2021). Value Stream Mapping in Construction 3D Printing: A Case Study at COBOD (Master's thesis, Aalborg University).
- ISO. (2015). ISO 9001:2015 Quality management systems, Requirements. International Organization for Standardization.
- Vries, H. J. de (1999). Standardization: A business approach to the role of national standardization organizations. Kluwer Academic Publishers.
- Rother, M., & Shook, J. (1999). Learning to See: Value Stream Mapping to Create Value and Eliminate Muda. Lean Enterprise Institute.
- Womack, J. P., Jones, D. T., & Roos, D. (1990). The Machine That Changed the World: The Story of Lean Production. Rawson Associates.

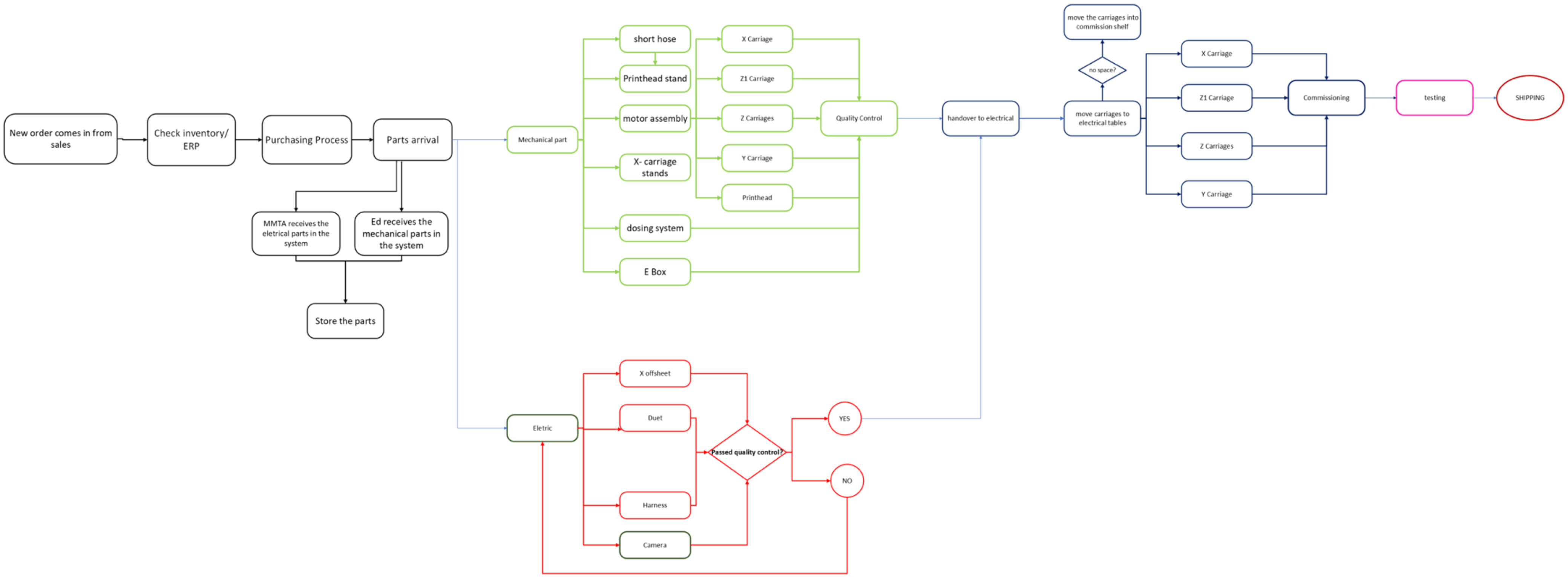
Online Sources

- https://cobod.com/solution/bod2/specifications/
- https://businessmap.io/lean-management/what-is-lean-management
- https://www.lean.org/explore-lean/what-is-lean/
- https://www.isixsigma.com/dictionary/poka-yoke/
- https://chools.in/wp-content/uploads/2021/03/Spaghetti-Diagram-1.pdf
- https://www.slideegg.com/value-stream-mapping-template?srsltid=AfmBOoqGpM4caDcRDUhFR17CxVxcUehEq7mdCbvTnn2DhEGUrpUhzQ86
- https://clubkaizenblog.wordpress.com/2023/08/20/sipoc-six-sigma-methodology/

Table of figures

Tables

APPENDIX A



New order comes in from sales
Check inventory/ ERP
Purchasing Process
Parts arrival
MMTA receives the eletrical parts in the system
Ed receives the mechanical parts in the system
Store the parts
Mechanical part
short hose
Printhead stand
motor assembly
X- carriage stands
dosing system
E Box
X Carriage
Z1 Carriage
Z Carriages
Y Carriage
Printhead
Quality Control
handover to electrical
move the carriages into commission shelf
no space?
move carriages to electrical tables
X Carriage
Z1 Carriage
Z Carriages
Y Carriage
Commissioning
testing
SHIPPING
Eletric
X offsheet
Duet
Harness
Camera
Passed quality control?
YES
NO

APPENDIX B

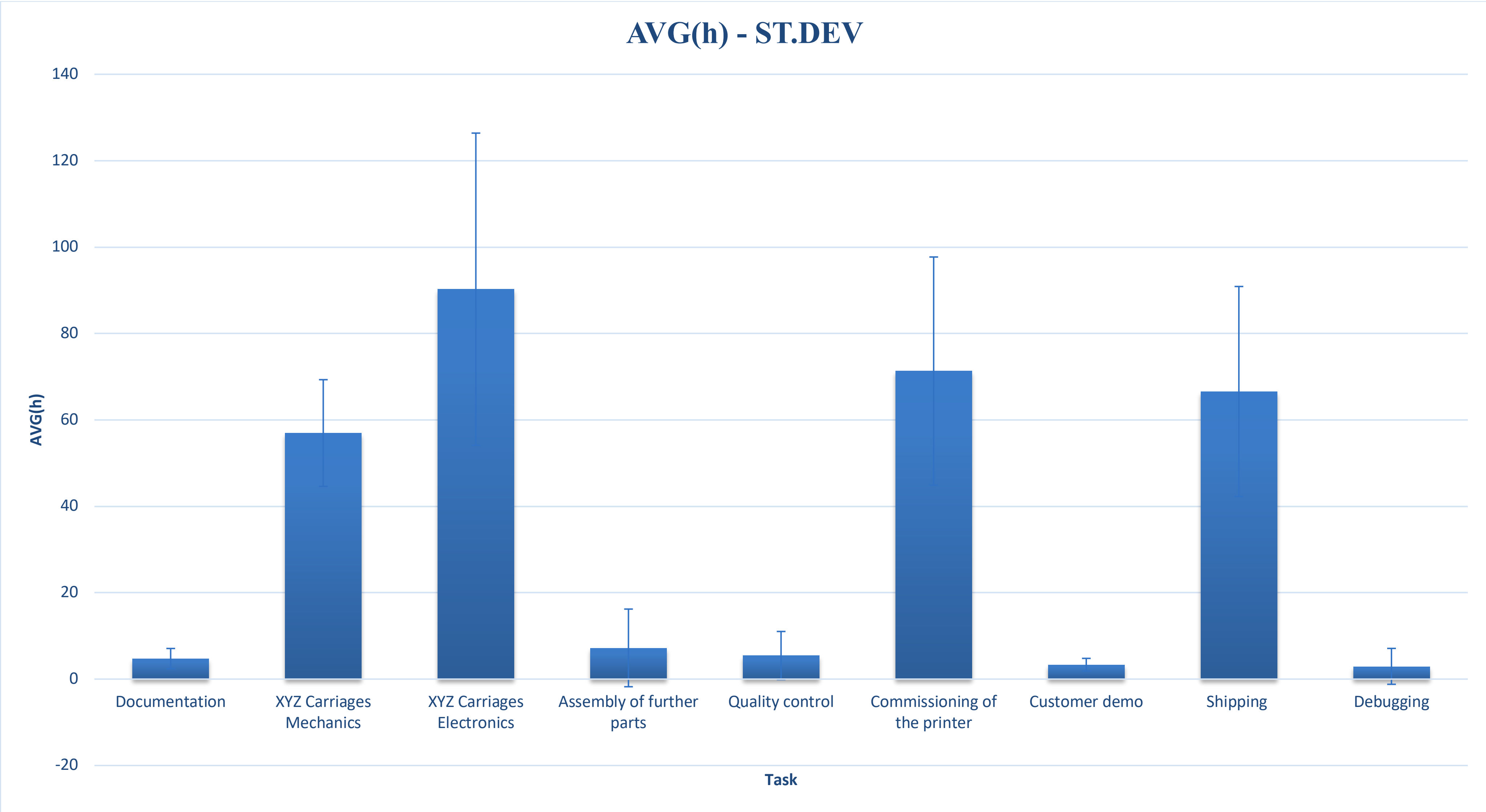
PRINTER	Documentation	XYZ Carriages Mechanics	XYZ Carriages Electronics	Assembly of further parts	Quality control	Commissioning of the printer	Customer demo	Shipping	Debugging	TOT (H) each printer
BOD2-582	4	60	22	2	0	65	5,18	43,15	2,07	203,4
BOD2-433	4	54	72,6	0	0,62	72,42	2,5	29,4	2	237,54
BO2-674	4,25	60	87,87	2	2,5	57,8	5,5	41,53	1,25	262,7
BOD2-583	5,2	57	119,98	0,33	9,083	30,83	4,3	79,78	2,07	308,573
BOD2-583	4,32	45	89,1	4,83	3,8	79	4	99,5	2	331,55
BOD2-654	4,75	65	70,8	0	2,25	74,4	3	91,02	1	312,22
BOD2-684	4,95	70	72,12	3,27	4,47	52,58	2	44,53	1,5	255,42
BOD2-443	4,75	67,26	230	12,38	5,35	60	4	36,61	0	420,35
BOD2-583	3	55,22	112,47	3,6	6,33	87,97	2,4	86,08	1,75	358,82
BOD2-543	5,58	43,3	92,78	22,25	9,55	69,75	3	57,97	5,33	309,51
BOD2-554	7	50	81,87	5,02	5,73	34,75	0	44,92	9,67	238,96
BOD2-553	1,5	54,5	70,8	0	9,13	60,98	2	43,15	0,83	242,89
BOD2-584	3	56	89	4,36	2,6	71,58	0	71,35	0	297,89
BOD2-554	15	64,3	70,8	9,6	4,25	79,5	4	92,55	18,17	358,17
BOD2-6104	3,3	60	83,12	11,4	9,22	76,03	4,2	51,05	0	298,32
BOD2-584	2	63	85	22,5	8,6	75,7	3,4	95,92	8,5	364,62
BOD2-553	2	60	92	0,61	0,65	66,65	3,4	72,9	2,5	300,71
BOD2-322	5,42	44	58,3	13,13	5	71,38	2	69,82	0	269,05
BOD2-553	4,2	54	92	0	4,68	87,48	6	74,02	0,82	323,2
BOD2-592	5,57	60	93,33	34	7,66	155,33	3,4	96,85	5	461,14
BOD2-554	6,75	57,4	65	31,42	1,7	62,83	2,6	58,65	0	286,35
BOD2-582	5,5	60	70,8	3,97	1,03	52,7	4,5	51,78	2,77	253,05
BOD2-554	4,2	59	79,78	11	7,75	60,98	3,4	37	2	265,11
BOD2-553	4,2	48,4	94,9	3,91	8,11	60	2,3	87,66	0	309,48
BOD2-554	5,4	54	91	4,33	5,58	130,8	4,3	117,83	0	413,24
BOD2-582	2,3	60	80	0	4,05	95,3	4,3	76,26	0	322,21
BOD2-684	5,7	65	149	4,3	1,93	106,78	3,5	57,15	1	394,36
BOD2-552	6,07	44	51,43	5,47	4,12	61	4	43	0	219,09
BOD2-6174	4,4	80	151,2	0,67	30,92	15,67	5,67	110,88	12,05	411,46
BOD2-582	5,5	83	70,8	3,52	0,62	61	3,5	60,73	2,93	291,6
CRETECH	3	12,52	108,06	4	2,01	74,03	0,83	40,63	6,3	251,38

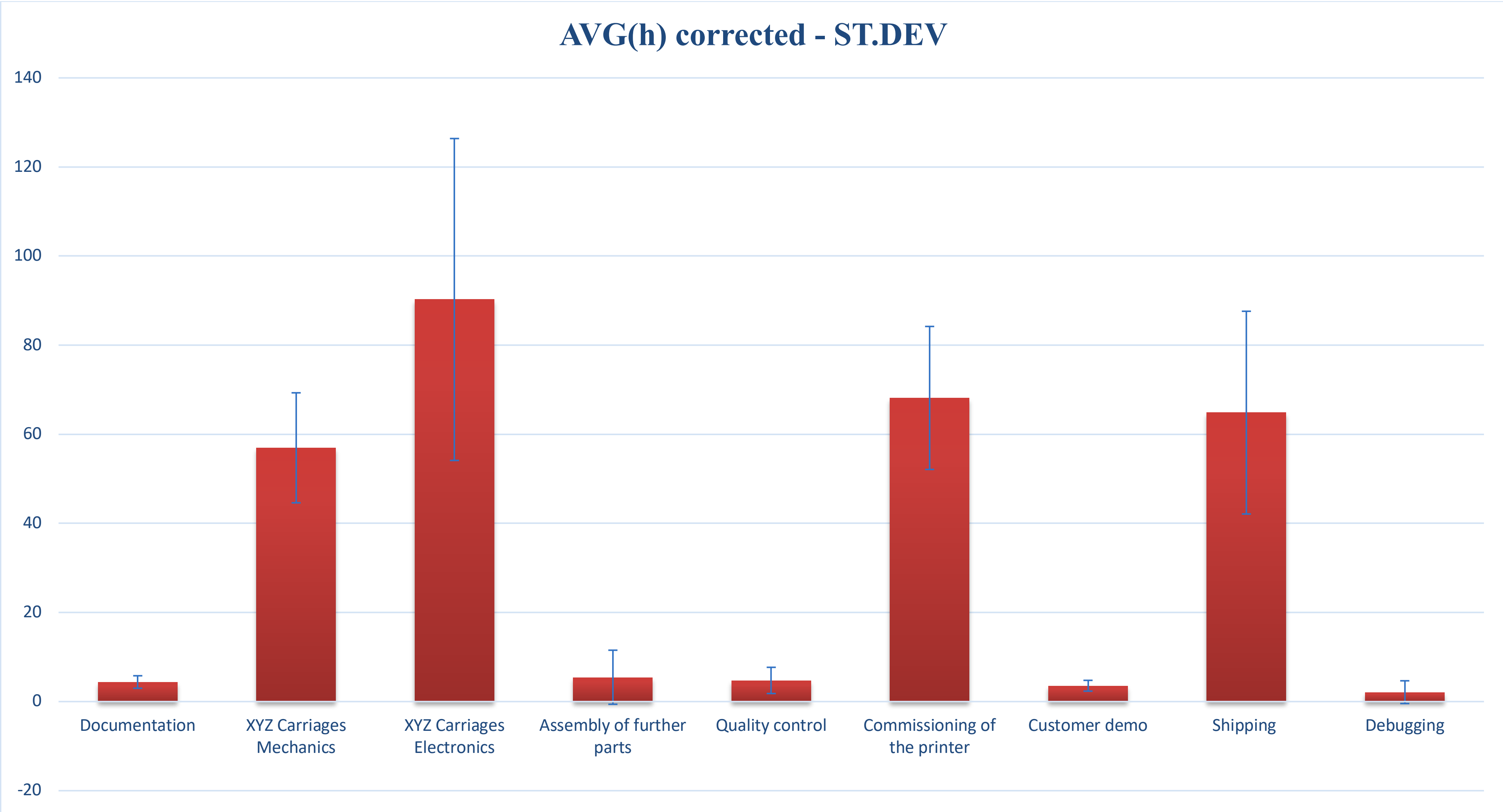
Z-SCORE ANALYSIS AND THE DEFINITION OF OUTLIERS

PRINTER	Documentation	XYZ Carriages Mechanics	XYZ Carriages Electronics	Assembly of further parts	Quality control	Commissioning of the printer	Customer demo	Shipping	Debugging
BOD2-582	-0,313	0,2459	-1,8891	-0,5810	-0,9816	-0,2384	1,2613	-0,9634	-0,2124
BOD2-433	-0,313	-0,2401	-0,4886	-0,8035	-0,8702	0,0425	-0,5643	-1,5290	-0,2292
BO2-674	-0,207	0,2459	-0,0660	-0,5810	-0,5323	-0,5111	1,4792	-1,0300	-0,4098
BOD2-583	0,197	0,0029	0,8227	-0,7668	0,6511	-1,5322	0,6618	0,5434	-0,2124
BOD2-583	-0,177	-0,9692	-0,0320	-0,2661	-0,2986	0,2916	0,4575	1,3546	-0,2292
BOD2-654	0,006	0,6509	-0,5385	-0,8035	-0,5772	0,1175	-0,2237	1,0058	-0,4700
BOD2-684	0,091	1,0559	-0,5019	-0,4397	-0,1781	-0,7087	-0,9049	-0,9066	-0,3496
BOD2-443	0,006	0,8340	3,8678	0,5739	-0,0200	-0,4278	0,4575	-1,2324	-0,7108
BOD2-583	-0,738	-0,1413	0,6148	-0,4030	0,1562	0,6313	-0,6324	0,8026	-0,2894
BOD2-543	0,359	-1,1069	0,0699	1,6721	0,7350	-0,0586	-0,2237	-0,3538	0,5726
BOD2-554	0,963	-0,5641	-0,2321	-0,2450	0,0483	-1,3838	-2,2672	-0,8906	1,6177
BOD2-553	-1,376	-0,1996	-0,5385	-0,8035	0,6595	-0,3907	-0,9049	-0,9634	-0,5110
BOD2-584	-0,738	-0,0781	-0,0347	-0,3184	-0,5143	0,0107	-2,2672	0,1966	-0,7108
BOD2-554	4,364	0,5942	-0,5385	0,2646	-0,2177	0,3106	0,4575	1,0687	3,6645
BOD2-6104	-0,611	0,2459	-0,1975	0,4649	0,6757	0,1792	0,5937	-0,6384	-0,7108
BOD2-584	-1,163	0,4889	-0,1454	1,6999	0,5642	0,1667	0,0488	1,2073	1,3360
BOD2-553	-1,163	0,2459	0,0483	-0,7356	-0,8648	-0,1760	0,0488	0,2604	-0,1088
BOD2-322	0,291	-1,0502	-0,8844	0,6574	-0,0829	0,0031	-0,9049	0,1337	-0,7108
BOD2-553	-0,228	-0,2401	0,0483	-0,8035	-0,1404	0,6127	1,8198	0,3065	-0,5134
BOD2-592	0,355	0,2459	0,0851	2,9795	0,3953	3,1818	0,0488	1,2456	0,4932
BOD2-554	0,856	0,0353	-0,6990	2,6924	-0,6761	-0,3206	-0,4962	-0,3258	-0,7108
BOD2-582	0,325	0,2459	-0,5385	-0,3618	-0,7965	-0,7042	0,7981	-0,6084	-0,0438
BOD2-554	-0,228	0,1649	-0,2899	0,4204	0,4114	-0,3907	0,0488	-1,2164	-0,2292
BOD2-553	-0,228	-0,6937	0,1286	-0,3685	0,4762	-0,4278	-0,7005	0,8676	-0,7108
BOD2-554	0,282	-0,2401	0,0206	-0,3217	0,0214	2,2530	0,6618	2,1086	-0,7108
BOD2-582	-1,036	0,2459	-0,2838	-0,8035	-0,2536	0,9088	0,6618	0,3986	-0,7108
BOD2-684	0,410	0,6509	1,6259	-0,3251	-0,6347	1,3435	0,1169	-0,3875	-0,4700
BOD2-552	0,567	-1,0502	-1,0746	-0,1949	-0,2411	-0,3899	0,4575	-0,9696	-0,7108
BOD2-6174	-0,143	1,8659	1,6868	-0,7290	4,5763	-2,1063	1,5950	1,8227	2,1908
BOD2-582	0,325	2,1089	-0,5385	-0,4119	-0,8702	-0,3899	0,1169	-0,2402	-0,0053
	-0,738	-3,6001	0,4928	-0,3584	-0,6203	0,1035	-1,7018	-1,0671	0,8062

DATA CORRECTED, ELIMINATION OF THE OUTLIERS

PRINTER	Documentation	XYZ Carriages Mechanics	XYZ Carriages Electronics	Assembly of further parts	Quality control	Commissioning of the printer	Customer demo	Shipping	Debugging	TOT (H) each printer
BOD2-582	4	60	22	2	0	65	5,18	43,15	2,07	203,4
BOD2-433	4	54	72,6	0	0,62	72,42	2,5	29,4	2	237,54
BO2-674	4,25	60	87,87	2	2,5	57,8	5,5	41,53	1,25	262,7
BOD2-583	5,2	57	119,98	0,33	9,083	30,83	4,3	79,78	2,07	308,573
BOD2-583	4,32	45	89,1	4,83	3,8	79	4	99,5	2	331,55
BOD2-654	4,75	65	70,8	0	2,25	74,4	3	91,02	1	312,22
BOD2-684	4,95	70	72,12	3,27	4,47	52,58	2	44,53	1,5	255,42
BOD2-443	4,75	67,26	230	12,38	5,35	60	4	36,61	0	420,35
BOD2-583	3	55,22	112,47	3,6	6,33	87,97	2,4	86,08	1,75	358,82
BOD2-543	5,58	43,3	92,78	22,25	9,55	69,75	3	57,97	5,33	309,51
BOD2-554	7	50	81,87	5,02	5,73	34,75		44,92	9,67	238,96
BOD2-553	1,5	54,5	70,8	0	9,13	60,98	2	43,15	0,83	242,89
BOD2-584	3	56	89	4,36	2,6	71,58		71,35	0	297,89
BOD2-554		64,3	70,8	9,6	4,25	79,5	4	92,55		325
BOD2-6104	3,3	60	83,12	11,4	9,22	76,03	4,2	51,05	0	298,32
BOD2-584	2	63	85	22,5	8,6	75,7	3,4	95,92	8,5	364,62
BOD2-553	2	60	92	0,61	0,65	66,65	3,4	72,9	2,5	300,71
BOD2-322	5,42	44	58,3	13,13	5	71,38	2	69,82	0	269,05
BOD2-553	4,2	54	92	0	4,68	87,48	6	74,02	0,82	323,2
BOD2-592	5,57	60	93,33		7,66		3,4	96,85	5	271,81
BOD2-554	6,75	57,4	65		1,7	62,83	2,6	58,65	0	254,93
BOD2-582	5,5	60	70,8	3,97	1,03	52,7	4,5	51,78	2,77	253,05
BOD2-554	4,2	59	79,78	11	7,75	60,98	3,4	37	2	265,11
BOD2-553	4,2	48,4	94,9	3,91	8,11	60	2,3	87,66	0	309,48
BOD2-554	5,4	54	91	4,33	5,58		4,3		0	164,61
BOD2-582	2,3	60	80	0	4,05	95,3	4,3	76,26	0	322,21
BOD2-684	5,7	65	149	4,3	1,93	106,78	3,5	57,15	1	394,36
BOD2-552	6,07	44	51,43	5,47	4,12	61	4	43	0	219,09
BOD2-6174	4,4	80	151,2	0,67			5,67	110,88		352,82
BOD2-582	5,5	83	70,8	3,52		61	3,5	60,73	2,93	290,98
CRETECH	3	12,52	108,06	4	2,01	74,03	0,83	40,63	6,3	251,38


AVG(h) - ST.DEV
140
120
100
80
60
40
20
0
-20
AVG(h)
Documentation
XYZ Carriages Mechanics
XYZ Carriages Electronics
Assembly of further parts
Quality control
Commissioning of the printer
Customer demo
Shipping
Debugging
Task


AVG(h) corrected - ST.DEV
140
120
100
80
60
40
20
0
-20
Documentation
XYZ Carriages Mechanics
XYZ Carriages Electronics
Assembly of further parts
Quality control
Commissioning of the printer
Customer demo
Shipping
Debugging

APPENDIX C

1. Internal Optimization

Within the activities of your department, which tasks do you believe have the greatest potential for optimisation in terms of time, resources, or quality of output?

- **Edgar:** Receipt and distribution of parts to their designated locations.
- **Mathias Andersen (Responsible of Electrical Dept.):** Producing wire harnesses. We have several different layouts of similar, if not the same, components that require custom harnesses. This could be standardised and simplified.
- **Edoardo Angioni (Logistics Coordinator):** Factory Acceptance Test procedure (resources); warranty shipment process (ERP and inventory); warehousing and picking (ERP).
- **Ole Ellinghausen (Head of Production):** The ad-hoc shipment process, which needs better planning and cost reduction. Also, strengthening team motivation and commitment.
- **Ismet Atacan (Industrial Operator):** Purchase orders, item selection, shipments, and printer assembly.

2. Time-wasting activities

In your experience, which activities generate the most time waste (waiting, rework, searching for materials, corrections), and in which stages do they most frequently occur?

- **Edgar:** Meetings, pointless meetings. The biggest delays come from missing parts in assembly (can delay by about a week) and poor R&D work on new parts that do not fit or require modification.
- **Mathias Andersen:** Posting assembly BOMs that are not updated with new parts or bin codes; manual corrections consume time.
- **Edoardo Angioni:** Cleaning threads of powder-coated parts; manual creation of shipping documentation; setup and take down of printers in commissioning.

- **Ole Ellinghausen:** When items are not in stock despite ERP showing availability, the whole process restarts and time is lost.
- **Ismet Atacan:** Waiting for the correct item stops production; ordering wrong items can also halt production or cause customer issues.

3. Causes of delays

What are the main causes of delays or slowdowns in the workflow (e.g. lack of materials, assembly errors, missing documentation, handovers with other departments)?

- **Edgar:** Badly handled stock of required parts; bad designs of parts; poor supplier production.
- **Mathias Andersen:** Lack of parts and incomplete documentation, often from rushed handovers or missing updates.
- **Edoardo Angioni:** Poor documentation of new products, late ordering or supplier delays, frequent changes in priorities from management.
- **Ole Ellinghausen:** Lack of materials, assembly errors, missing documentation, and departmental handovers.
- **Ismet Atacan:** Poor restock organisation and poor communication between departments; lack of standardisation.

4. Impact on quality

At which points in the process do you think defects or rework most often arise? Are there activities that you feel have a particularly strong impact on the final quality of the printer?

- **Edgar**: Mechanical assembly, when parts do not fit or are incorrectly produced.
- **Mathias Andersen:** Assembly stage, when manuals are vague or outdated.
- **Edoardo Angioni:** FAT stage, where incoming parts (especially sheet metal) often show quality issues; missing items and QC issues not fixed before shipping.
- **Ole Ellinghausen:** Commissioning stage, when missing elements are discovered before loading into containers.
- **Ismet Atacan:** Testing/commissioning phase; also at customer sites due to different environments and missing/wrong items.

5. Improvement priorities

If you had to identify one or two improvement priorities for your department, what would they be, and why?

- **Edgar:** More time for quality control and documentation of incoming parts; more time for R&D testing.
- **Mathias Andersen:** Better documentation and ERP implementation for part-picking.
- **Edoardo Angioni:** Improved documentation and use of ERP to automate tasks; reduce FAT workload with test benches; better alignment of priorities across departments.
- **Ole Ellinghausen:** Strengthen team motivation and engagement.
- **Ismet Atacan:** Standardisation and automation of processes (ordering and production).

6. Relocation to the new facility (optional)

With the upcoming relocation to the new production site, which organisational or process changes do you consider essential to reduce inefficiencies and increase workflow stability?

- **Edgar:** Improve overall flow from part receipt to packing and shipping; better logistics and organised part locations.
- **Mathias Andersen:** Restructure BOMs and implement controlled parts allocation; improve productivity by reducing missing parts.
- **Edoardo Angioni:** Improve BOM creation, revision, and ERP understanding; merge inventories with fixed bin locations; ensure correct handling of Ex Works terms.
- **Ole Ellinghausen:** Establish a clear and efficient system and maintain it consistently.
- **Ismet Atacan:** Clear workflow and item lists; ERP system that automatically orders items; improved spatial layout for better communication.

Ringraziamenti

Con quest'ultima pagina si conclude una delle fasi più gratificanti e al tempo stesso più sfidanti della mia vita, un percorso che mi ha permesso di crescere, di imparare ad essere costante, ad impegnarmi e a diventare sempre più ambiziosa.

Il mio pensiero più grande va alla mia famiglia, che mi ha insegnato a non arrendermi mai, a credere nei miei obiettivi e a cercare di migliorarmi ogni giorno. Alla mia mamma e al mio papà, che hanno reso tutto questo possibile; a Sara e Sofia, la mia sicurezza, che ogni giorno mi ricordano il valore della semplicità.

Un pensiero speciale va ad Angela, che con il suo esempio e il suo supporto mi ha insegnato che insieme siamo capaci di tutto.

Un ringraziamento ad Alessandro, con cui ho condiviso questo percorso: insieme abbiamo affrontato e superato ogni sfida, questo traguardo è anche il suo.

La mia riconoscenza va anche alla Prof.ssa Giulia Bruno, per il prezioso supporto e la guida costante nella stesura di questa tesi, e ad Ole, che ha creduto in me e mi ha offerto l'opportunità di vivere un'esperienza straordinaria a Copenhagen, trasformando un sogno in realtà.

Infine, rivolgo un pensiero a me stessa, per aver avuto il coraggio di credere in questo percorso e la determinazione di portarlo a termine con passione e dedizione.